Research and Development Plan for the Supernova / Acceleration Probe (SNAP)

The SNAP Collaboration

22 June 2002
Revised 5 July 2002
Revised 25 September 2002

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1.1 Introduction

Our picture of the origin and nature of the universe has been transformed in the past few years by the first precision measurements of the fundamental cosmological parameters. Contrary to the expectations of the theoretical community that the mass density would equal the critical density, balancing the universe between eternal expansion and ultimate contraction, measurements carried out by two different groups studying supernovae concluded that the universe is expanding at an ever increasing rate and established a non-zero value for the cosmological constant. Recent independent data from cosmic microwave background measurements and from galaxy surveys are consistent with the results from the supernova experiments. For example, the 2002 results from the Cosmic Background Imager and the Two Degree Field Galaxy Redshift Survey also predict that two-thirds of the critical density resides in a cosmological constant.

These results have caused a great deal of speculation in the theoretical community and sparked a number of new theories regarding the so-called "dark energy" that is driving the accelerating expansion of the universe. Understanding the nature of the dark energy is one of the key science goals identified by the Turner panel of the NAS and by the High Energy Physics Advisory Panel Subcommittee for Long-Range Planning.

In order to carry out more precise measurements of the cosmological parameters and determine the equation of state of the dark energy, we have proposed a dedicated satellite-based experiment, the Supernova Acceleration Probe (SNAP). SNAP is a ~2-meter satellite telescope that will obtain a high statistics (~2000) calibrated data set of Type Ia supernovae with redshifts $z \leq 1.7$ and excellent control over systematic errors. To obtain high signal-to-noise, calibrated light curves and spectra for each supernova, SNAP is instrumented with a 0.7-square degree pixel-based imager with sensitivity to wavelengths ranging from 350–1700 nm, a near-UV to near–IR spectrograph and precision star guider CCDs. These instruments are integrated on a common focal plane. From these data we expect to measure the mass density of the universe to 2%, the density of dark energy driving the acceleration of the universe to 5%, and its equation of state to 5%. Time variation in the equation of state, a key attribute distinguishing other vacuum energies from a cosmological constant, could be detected. Detailed systematic studies will be carried out to account for potential biases or sources of error due to interstellar dust, galactic environment, *etc*.

In addition to the primary scientific goals of measuring the cosmological parameters, a rich program of auxiliary science can be carried out with SNAP's comprehensive wide field data set. This includes study of weak and strong gravitational lensing that probe the dark matter content and distribution, time variable objects such as active galactic nuclei, gamma ray burst afterglows, outer solar system bodies, and the detailed population and distribution of galaxy types and stellar evolution.

In this document we summarize the work that has been accomplished since the January 2001 review and describe the remaining R&D necessary to prepare a conceptual design and initiation of the engineering and design phase (CD1 approval). In Section 2, the R&D plan for the SNAP instrumentation suite is described. Section 3 discusses the development of the instrument calibration plan. Sections 4-6 are devoted to computing, telescope and spacecraft R&D plans. Sections 7 and 8 describe the system engineering and project management for the R&D phase. Schedules for completion of the R&D and manpower estimates are incorporated within each section, while cost estimates are collected in a separate document.

1.2 High-Level Mission Requirements

The high-level mission requirements can be divided into two categories: requirements derived from the scientific goals of the project, and requirements derived from the need to withstand the rigors of launch and operation in space. These requirements and their derivation from the SNAP science goals are described in greater detail in the SNAP Mission Definition and Requirements Document. Here we provide an overview of the most important requirements.

1.2.1 Science-driven instrument requirements

The SNAP satellite telescope and instrumentation suite is designed to provide observational data on a high statistics sample of supernova consisting of the following elements:

1. Early detection of supernova.
2. B-band rest-frame photometry to follow the supernova light curve.
3. Supernova color at peak and near-peak brightness.
4. Optical and IR spectra at peak brightness to classify the supernova.
5. Photometric redshifts of the host galaxies prior to supernova follow-up.
6. Medium resolution spectra/photometry for a limited subset of supernovae over the full light-curve.

Each of these observational requirements translates into a set of explicit requirements on the telescopes and instruments, also detailed in the SNAP Mission Definition and Requirements Document.

1.2.2 Requirements for operation in space

Launch and operation in space also impose requirements on the SNAP instrumentation suite and telescope. Many of these requirements involve design trade-offs and are still under development.

The maximum launch payload limits both size and weight. At this time we are contemplating launch aboard a Delta IV-M, which can lift a maximum of 2800 kg. The Delta IV-M offers a 4-meter diameter payload fairing, which in principle could accommodate up to a 2.4-meter telescope.

Available power on the spacecraft will be limited to what can be provided by on-board solar panels, estimated at approximately 300-400 watts average power load.

Thermal management is an important issue affecting all components. In the SNAP working concept, the instrument CCDs for optical and IR imaging will operate at 140 K for best performance, while the telescope will be maintained at room temperature in order to simplify pre-flight testing. This approach to thermal management is one of the recommendations of a trade study conducted at NASA-Goddard in the past year.

Reliability is a major concern; all instruments must be space-qualified, demonstrate a minimum mean time to failure, and incorporate redundancy where possible. We are designing for a minimum of 4 years of operation.

1.3 R&D goals

The R&D phase has five main goals:

1. Develop detailed requirements documents that will drive the later design and engineering phase of the project.
2. Develop and optimize concepts for all components to sufficient detail to insure a credible cost and schedule at CD1.
3. Identify the areas of highest risk and initiate design efforts and prototyping to mitigate cost and schedule risk during the construction phase.
4. Identify long-lead procurement items that could pace the final completion of the project, and initiate early discussions with potential vendors to minimize schedule and cost risk.

5. Identify and resolve instrumentation issues that affect the spacecraft and telescope design so that development can proceed in parallel.

The vast majority of R&D issues addressed in this proposal are paper studies that will document requirements, develop implementation concepts to meet the requirements, and simulate or otherwise validate these concepts. We will research existing or planned solutions that meet our requirements where these can be identified, and develop common solutions for all of the SNAP instruments wherever feasible. Scientific trade-off studies between competing designs or options will be carried out to determine the optimum design to meet SNAP's mission requirements.

Preliminary design work and prototyping will be initiated only where high risk and/or long lead items are identified with associated cost and schedule risks to the project. For example, the CCDs and associated readout electronics represent a new, attractive but unproven technology that will benefit from early design and prototype effort. The telescope, on the other hand, requires no real R&D because its optical parameters fall within the range of previously completed projects; nevertheless, a long lead time and high cost are associated with its procurement.

Section 2. Instrument R&D Plan

This section describes the R&D plan for the SNAP instrument suite. We start with the conceptual design of the instrument. While this working concept will be subject to further scrutiny and optimization, it provides a solid foundation for a feasible and self-consistent observation strategy that realizes the primary scientific goals of SNAP. It also forms the basis for a program of limited and focused R&D that will lead to reliable cost and schedule estimates and a Conceptual Design Review (CDR) in two years. Next, we present an overview of the organizational structure and procedures in place to manage the R&D effort. Finally, we describe the evolution of our focal plane concepts.

The remaining sections describe the detailed R&D plans for the components that make up the SNAP instrument suite: imager, spectrograph, and electronics and data acquisition. Each section includes a review of progress in the past year, a discussion of the main R&D issues and goals, and a summary of CDR planning activities, long-lead procurements, risk assessment, schedule, milestones and manpower. R&D costs are summarized in a separate document.

Design and prototyping work for the SNAP instrument suite during the R&D phase is limited to the following areas:

- Characterization of commercially available IR detectors with 1.7 μm cutoff.
- Completion of development and commercialization of a new type of optical CCD featuring extended red response and enhanced radiation tolerance.
- Design of an integral field unit for the spectrographs.
- Development of custom integrated circuits for sensor readout.

2.1 Instrument Conceptual Design

In the past 18 months we have conducted a scientific and technical trade study to determine the optimal configuration of the SNAP instrument suite. Several options were studied and are discussed below. The conclusion is that a wide-field integrated optical to NIR imager with fixed filters provides the most efficient approach to collecting a high statistics, comprehensive and precisely calibrated data set of SNe, while meeting our criteria for technical feasibility, cost and schedule. A spectrograph is mounted on the backside of the focal plane and accesses light though a port in the focal plane. The observational strategy involves visiting the SNAP observation field every four days and stepping the focal plane across the field to collect a series of fixed duration exposures. Ground-based analysis of the transmitted data identifies Type Ia SNe and determines galaxy redshifts; with this information, SNe are selected for targeted spectrographic measurements at maximum brightness.

The present working concept of the SNAP instrument package is shown in Figure 1 and Figure 2 and consists of the following elements:

- *Imager.* The imager contains optical and IR sensors integrated on a common focal plane operated at 140 K, which is compatible with passive cooling. Fixed filters provide continuous overlapping photometry in nine bands over the visible and NIR wavelengths for B-band restframe measurements of SNe with redshifts up to 1.7. LBNL-developed CCDs cover 350 nm to 1000 nm. They are selected for their broad spectral response and high degree of radiation tolerance. A total of thirty-six, 3.5k $\times$ 3.5k, 10.5 μm CCD detectors are required. The NIR sensors are Rockwell MBE HgCdTe devices. Thirty-six 2k x 2k, 18 μm detectors will be used to cover the 900 nm to 1700 nm range.

- *Spectrograph.* Spectrographic information for each supernova at peak brightness is required. An instrument spanning the wavelength range of 350 nm to 1700 nm with a resolution $\lambda/\delta\lambda$ of 100 can measure all the relevant features of Type Ia SNe over this range. A two-channel spectrograph utilizes the same focal plane as the imager. The sensors for the spectrograph consist of an LBNL CCD for optical wavelengths and a HgCdTe device for the near infrared.

- *Star guider.* Four small high speed CCDs are also mounted on the focal plane to provide feedback to the spacecraft during shutter-open time to help the attitude control system achieve the required pointing stability during the several hundred to several thousand second exposures.

- *Electronics systems*. Four systems of components make up the electronics suite. The first system includes clock and bias voltage generation, analog signal processing, and digitizing for the sensors. In the case of the CCDs, we are exploring the use of custom integrated circuits (ASICs) for at least the analog processing and digitization. In the case of the HgCdTe devices, an effort has been mounted at Rockwell to provide an ASIC for the clocking and digitization. The second system funnels the data streams from the sensors into the spacecraft solid state recorder. This may entail lossless compression of the data if that function is not provided by the recorder. Third is the system that configures the electronics subsystems and monitors the instrument environment. Examples of this include setting operating voltages inside the front-end electronics and monitoring the sensor temperatures. The fourth system oversees the execution of the observation plan that performs such activities as opening and closing the shutter, cycling the calibration lamps, and transitioning the readout electronics from image capture to readout mode. As our concept evolves, it may turn out that the intelligence for controlling some or all of the above will fall in the domain of the spacecraft.

- *Mechanical systems*. The mechanical components of the instrument comprise a mechanical shutter, a combined function particle/thermal/stray-light shield, a 140 K cold plate to which the imager sensors and spectrograph are mounted, thermally isolating kinematic mounts by which the cold plate is attached to the telescope mechanical structure, flexible thermal links between the cold plate and the radiator, and the radiator itself that provides passive cooling of the cold plate and its sensors.

2.2 Instrument R&D Management Plan

The goal of the R&D period is to develop a conceptual design with an associated cost and schedule that can serve as the basis for the Conceptual Design Review (CDR). In addition, we seek to identify and mitigate project risk due to unproven technologies and long-lead procurements. The main deliverables of the R&D period are a Conceptual Design Report including a formal set of requirements linked to the science goals, a preliminary interface control document that defines system components and their interactions, a detailed schedule, and a reliable cost estimate.

The SNAP instrument R&D organization is shown in Figure 3. Six instrument working groups study CCDs, NIR sensors, the star guider, mechanical and thermal design, electronics, and the spectrograph. The instrument manager holds monthly meetings with the working group leaders to track progress and coordinate efforts. Within each working group, regular weekly meetings are held to present progress and discuss results. Schedule and budget for all instrument R&D activities are tracked by the instrument manager. Reviews are organized at the instrument level; for the R&D period, we foresee one major review for each of the working groups to scrutinize the requirements document and the preliminary conceptual design prior to the CDR.

2.3 Instrument Conceptual Design Evolution

An immutable aspect of SNAP operations is repetitive imaging of fixed regions of the sky. Transients identified as Type Ia supernova by ground analysis of the imaging data are targeted into a spectrograph near peak brightness. The repetitive imaging simultaneously accomplishes discovery and follow-up of supernovae using multiple filters.

The same set of instruments – visible and NIR imagers, spectrograph, and star guiders – is present in all the concepts. The SNAP instruments presented at the January 2001 review are reviewed in Figure 4. There the various components tapped the telescope light at a multitude of points, as is apparent in the figure. We developed several concerns with this legacy configuration:

- Multiple focal planes requiring simultaneous focus and focus stability.
- Multiple filter and shutter mechanisms.
- Non-overlapping fields of view (FOV) for the visible and NIR imagers.
- Small FOV for the NIR imager, consisting only of one or four sensors.
- Large observational inefficiency from targeting SNe onto the NIR imager.

One characteristic of the legacy concept was that it could be pointed anywhere in the sky to produce a complete set of multi-filter measurements in one or the other imager. Rotation of the satellite around the primary axis did not affect the observation plan.

Just prior to the January 2001 review we began to study an alternative concept in which all imager sensors, the spectrograph input, and the star guiders are mounted at a common focal plane. The following describes different strategies that we considered for deployment of sensors, filters, and shutters around an integrated focal plane. The distinctions between these strategies mainly concern the imagers and how to filter and shutter their light. The spectrograph imposes no preference for one solution over another.

One strategy involved different mixtures of visible and NIR sensors behind a filter wheel and shutter. We identified several difficulties with this strategy:

- Different FOV for visible and NIR.
- Time-consuming cross-measurement of stars at visible and NIR wavelengths, further complicated by the inefficient geometry of the annular focal plane.
- Large filter wheel, requiring each filter to be ~200 mm in diameter. Without multi-bandpass filters, one sensor or the other would be blind.

To deal with the latter issue, we considered a second strategy involving annular wedge filter wheels located above the focal plane. Figure 5 shows a focal plane concept in which the outer annulus contains CCDs and the inner annulus contains HgCdTe NIR sensors. Each annulus has its own filter annulus with filter areas weighted to achieve the required S/N in each bandpass (more red filter area to accommodate the lower photon flux in the z-shifted B-band spectrum of high z SNe). The figure also shows a novel shutter mechanism that was conceived to make unnecessary a single large shutter mechanism. (This is not essential; a single large shutter also would work.) A motivation for this design was to address actuator failure. Individual shutter flaps could be allowed to fail, and, if the filter wheels stuck, steering the satellite to move stars across the filters could partially save the mission. However, the visible and NIR FOV are still disjoint, and the first two difficulties identified for the initial strategy would still apply.

We did consider the option of using a single sensor maintaining sensitivity across the full wavelength span of interest, 400 nm to 1700 nm. This would allow all sensors to remain active at any filter setting and allow the overlap of visible and

NIR FOVs. However, the broad wavelength span coupled with a fixed pixel size dramatically impacted the SNAP mission. For efficient pixel use we have found that sampling the Airy diffraction disk with one pixel is sufficient (*i.e.*, a factor of two undersampling). We apply this at 1000 nm for the visible detectors and at 1700 nm for the NIR. A single pixel size at our present NIR 0.17 arcsec/pixel plate scale would require twice as many exposures (dithering) to generate the same photometric accuracy in the blue. The complementary approach would match the 0.1 arcsec/pixel plate scale of the visible imager. This would require a trebling of the focal plane area to cover the same FOV, or a 65% reduction of the FOV to maintain the same focal plane area.

All the single-focal-plane strategies described so far involve large, massive, untried filter wheels. We and external advisors viewed this as a high risk. Also, over the last year, the science team has concluded that each SNe needs to be measured with a larger number of filters in order to build light curves in multiple colors (dust extinction correction uses differences between pairs of filters). The blue end of the SNe spectra, restframe U-band, has grown in importance for classification as well as restframe R- and I-band. At high z, the population of non-Type Ia SNe is expected to be large, and false identification is expensive in time consumed for spectrographic measurement of high z objects. Measurements in the restframe R-band appear to provide a powerful handle on dust extinction determination. We reached the consensus that all objects need to be measured in all filters, visible and NIR. The above led us to consider a class of focal planes with fixed filters.

A simple example of a fixed filter focal plane is shown in Figure 6. A linear array of sensors with different filters is swept across a star field by steering the telescope. The actual motion is a series of steps, each step having a fixed exposure time. The number of steps within a filter determines the total integration time. Note that multiple steps within a filter facilitate standard techniques for optimizing photometric accuracy such as dithering. For example, four exposures within a filter could be offset precisely from each other by a fraction of a pixel size. A coarse hop to the next filter then would follow.

In this simple example, note that some filters are longer than others. This is a way to gain longer integration time in some filters, such as those in the red and NIR, where SNe signals are weaker. Here we also point out an inefficiency in any fixed filter scheme: stars are not measured in all filters both at the beginning and at the end of the scan. This inefficiency can be minimized but not eliminated by scanning a long, linear piece of the sky.

To populate a useful focal plane, a two- rather than a one-dimensional deployment of filters is required. It should be obvious that no array of square filters can repetitively measure the same patch of sky in all filters if the satellite rotates continuously relative to the observation fields. It is not a constraint, however, that the satellite continuously rotates. Even though SNAP has fixed, body mounted solar cells and a passive heat radiator, the satellite can be rotated ±45^{o} relative to normal Sun incidence on the solar panels. The satellite and focal plane can be held in fixed alignment relative to the observation field for three month periods after which the satellite is rotated 90^{o}. Figure 7 clarifies this point.

The constraint that the satellite be rotated be in 90^{o} increments requires the filter pattern to remain symmetric with respect to two orthogonal axes. Consider either of the filter arrays in Figure 8. Note that the arrays can be scanned though an observation field left-to-right, right-to-left, top-to-bottom, and bottom-to-top, and that a given star will be measured with each filter color but not necessarily the same physical filter. Note that any 90^{o} rotation of the filter array in Figure 9 can still measure the star field in all filter types.

A study was performed to determine the minimum filter set required. This is primarily determined by the precision needed for the so-called k-correction. Simply, this is the reconstruction of the restframe B-band light from a set of laboratory frame filter measurements. The study found that six visible filters and three NIR filters are sufficient if they are derived from a B-band filter with 1+z scaling of their wavelength centers and widths. Figure 8 shows an array of visible and NIR filters. To enhance the amount of NIR light that is integrated, the individual NIR filters have twice the area of the individual visible filters.

The HgCdTe sensor physical size is fixed by the vendor. We have control of the CCD size, so that it is possible to make the physical dimensions of the 6x6 CCD filter array equal to those of the 3x3 NIR filter array. Adopting this choice, there are only two low order solutions for populating our annular focal plane with these filter unit cells. Figure 10 shows the solution that makes most efficient use of the available FOV (the rejected solution is half as efficient). Figure 11 shows the underlying sensors assuming 3.5×3.5, 10.5 μm CCDs and $2k \times 2k$, 18 μm HgCdTe devices. The concept in Figure 10 can meet the photometric S/N requirements for SNAP from z<1.7 with four 300 s exposures in the visible, corresponding to eight 300 s exposures in the NIR. The results of a detailed simulation are presented elsewhere.

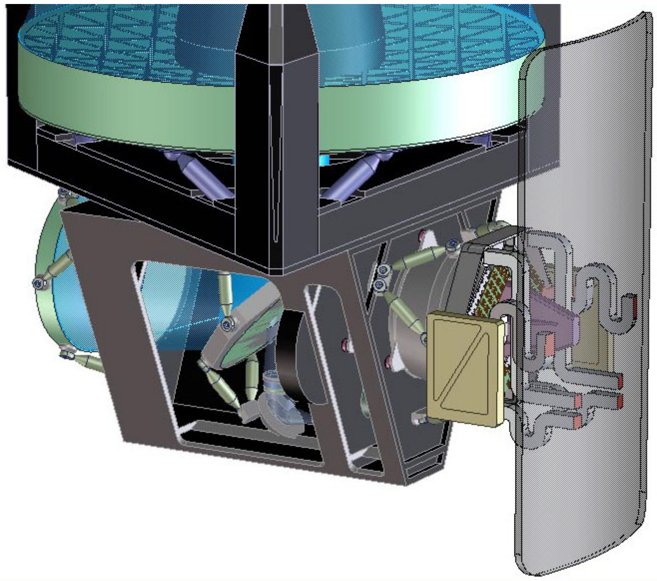


Figure 1. SNAP instrument installed in the optical bench.

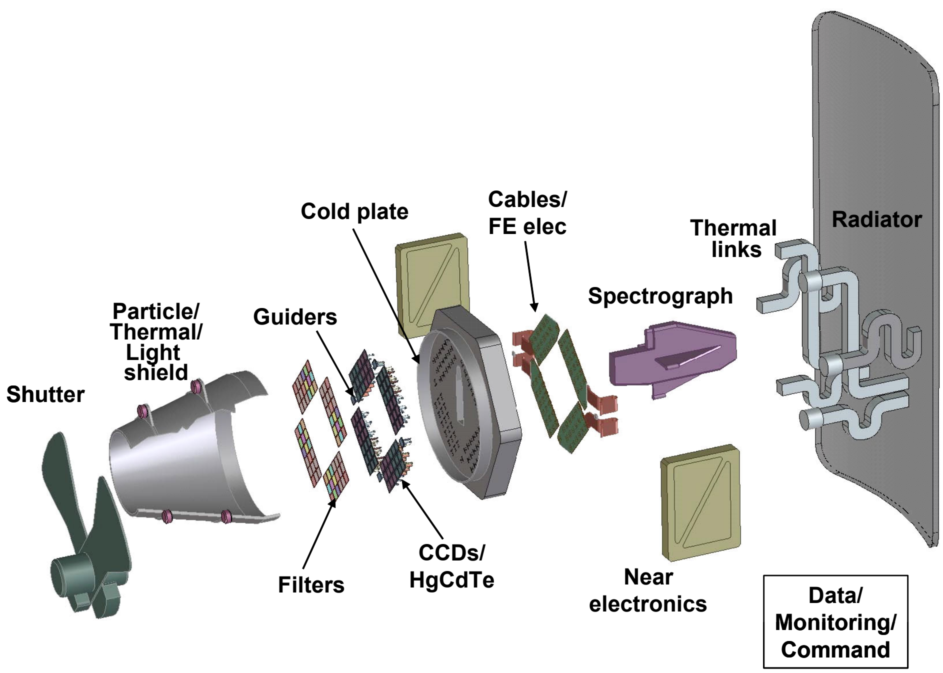


Figure 2. Exploded view of the SNAP instrument concept.

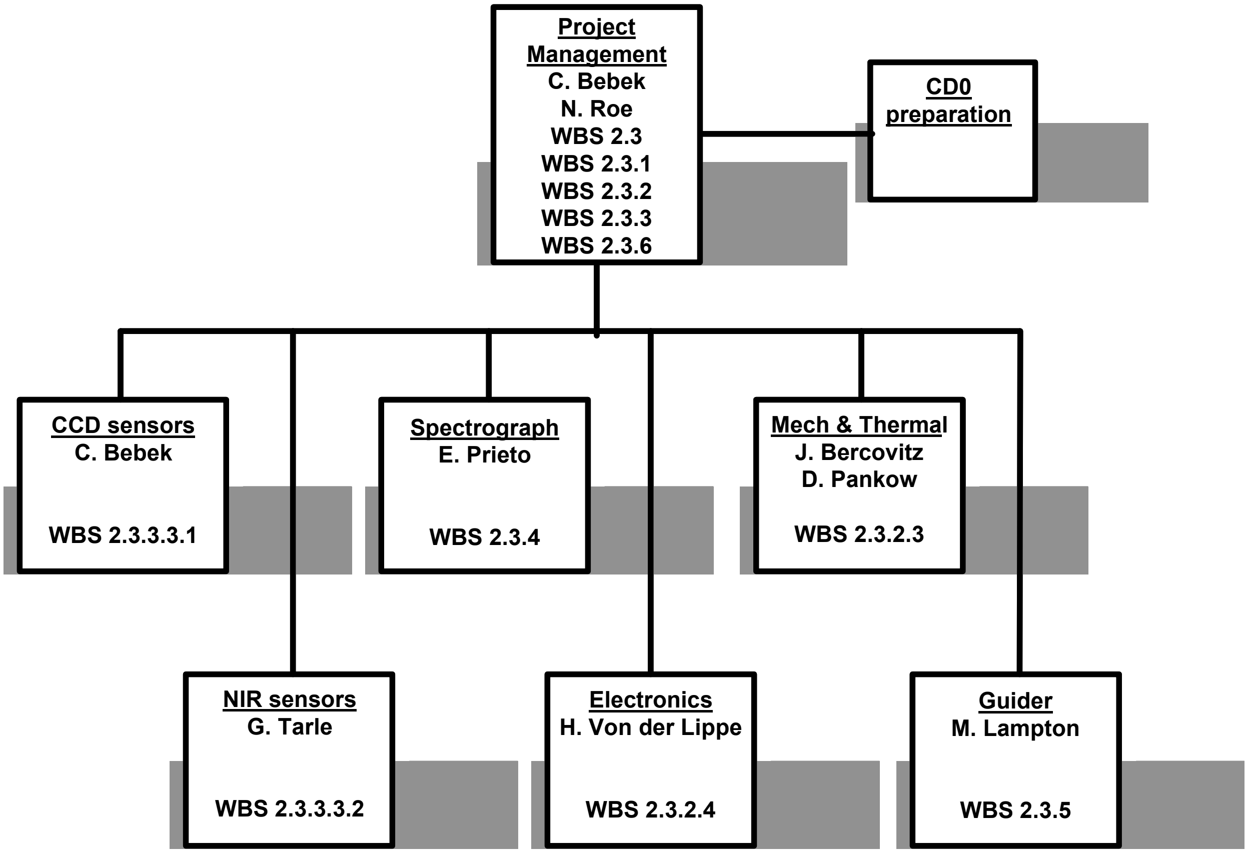


Figure 3. Management structure for the instrument R&D phase.

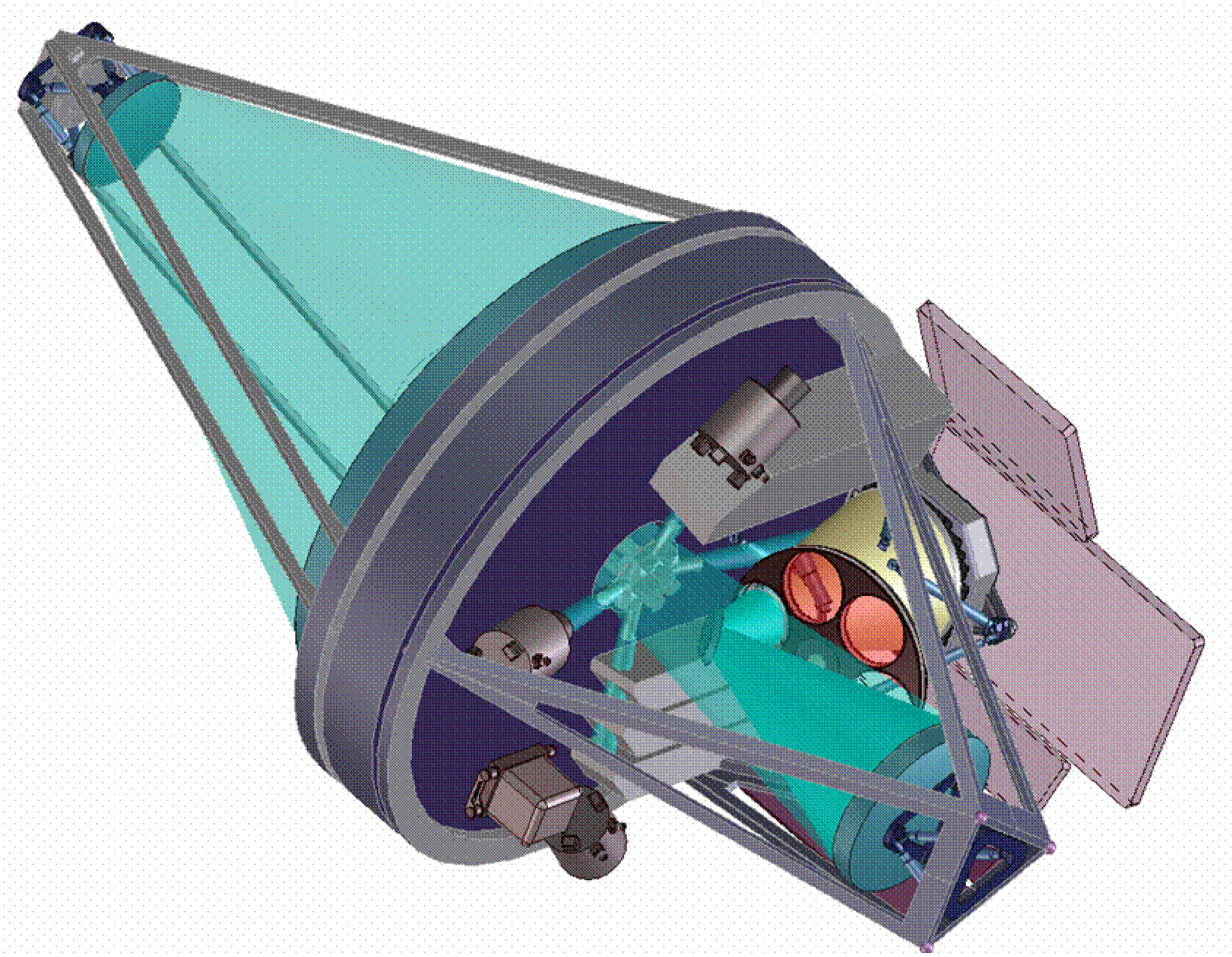


Figure 4. Obsolete instrument concept from January 2001. As can be seen, the discrete instruments (visible imager, NIR imagers, spectrographs, and star guiders are tapping different parts of the main telescope beam and must maintain their individual focuses.

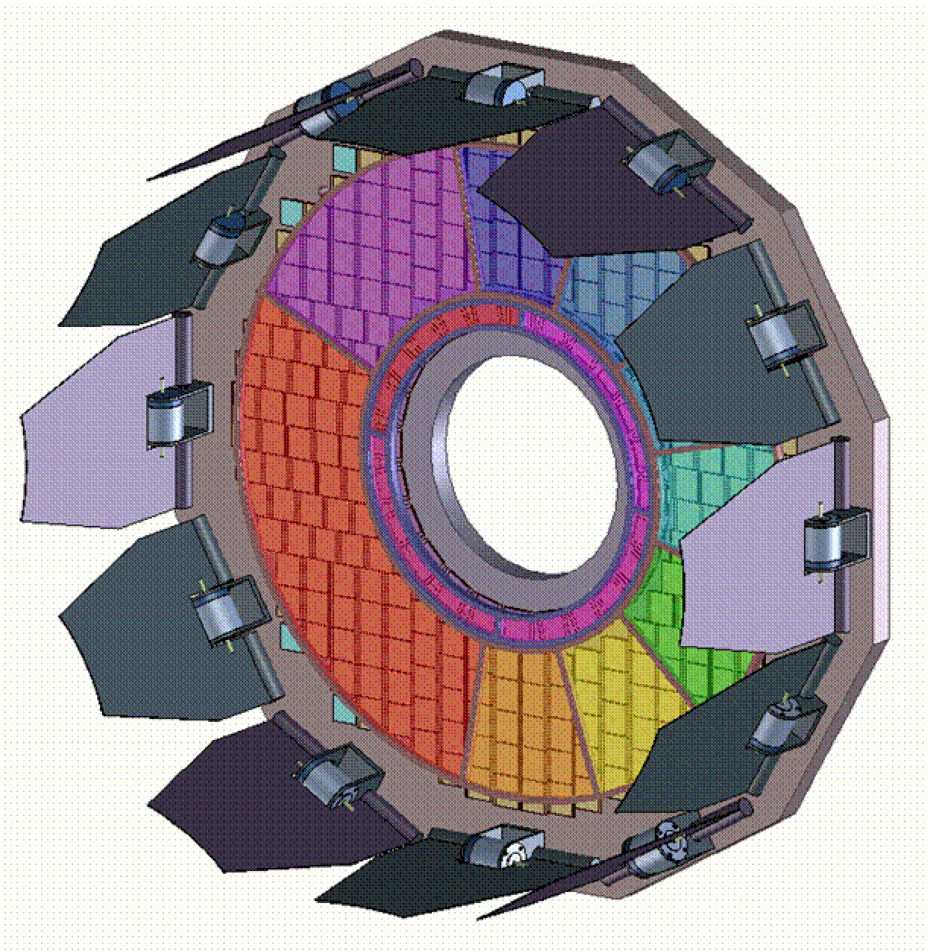


Figure 5. Obsolete instrument concept with visible imager sensors occupying the outer annulus and the NIR imager sensors occupying the inner annulus. In this concept, separate annular filter wedge wheels rotate above the two image planes. The relative area of the filters compensates for the decreasing intensity of reddened, high z supernovae. The flippers implement a shutter.

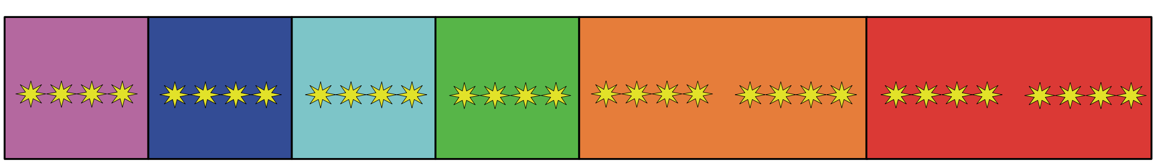


Figure 6. A simple example depicting a linear array of fixed filters. Shown are the positions of a single star as the filters are dragged past it.

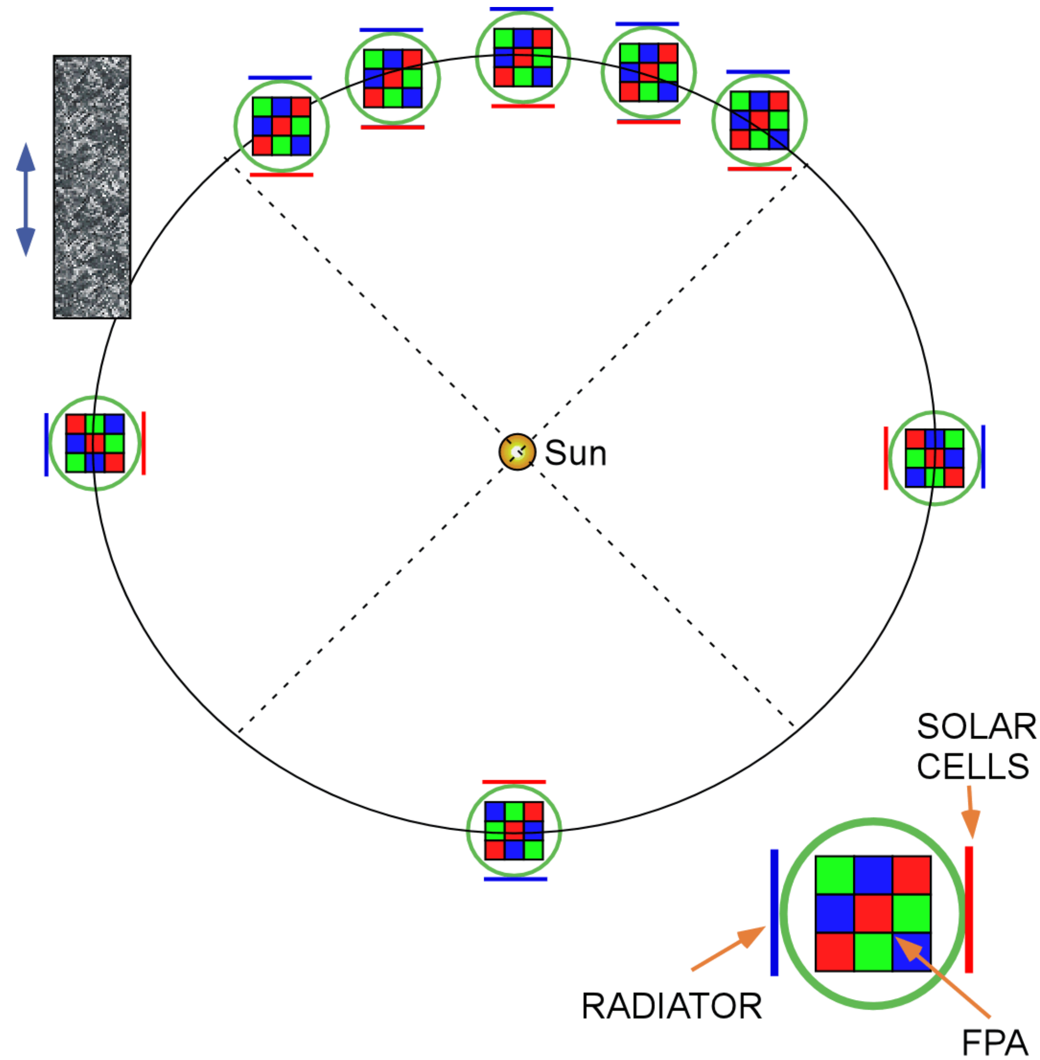


Figure 7. An illustration of the interaction between the satellite and its focal plane array, the orientation to the Sun, and an observation field (upper left). The upper arc shows how the satellite must rotate relative to the Sun to maintain the fixed filters in a constant orientation relative to the observation field. The left and right arcs show a 90° rotation to maintain the general orientation of the solar cells towards the Sun. The double arrow next to the observation field shows the direction in which the satellite is rocked to scan the field.

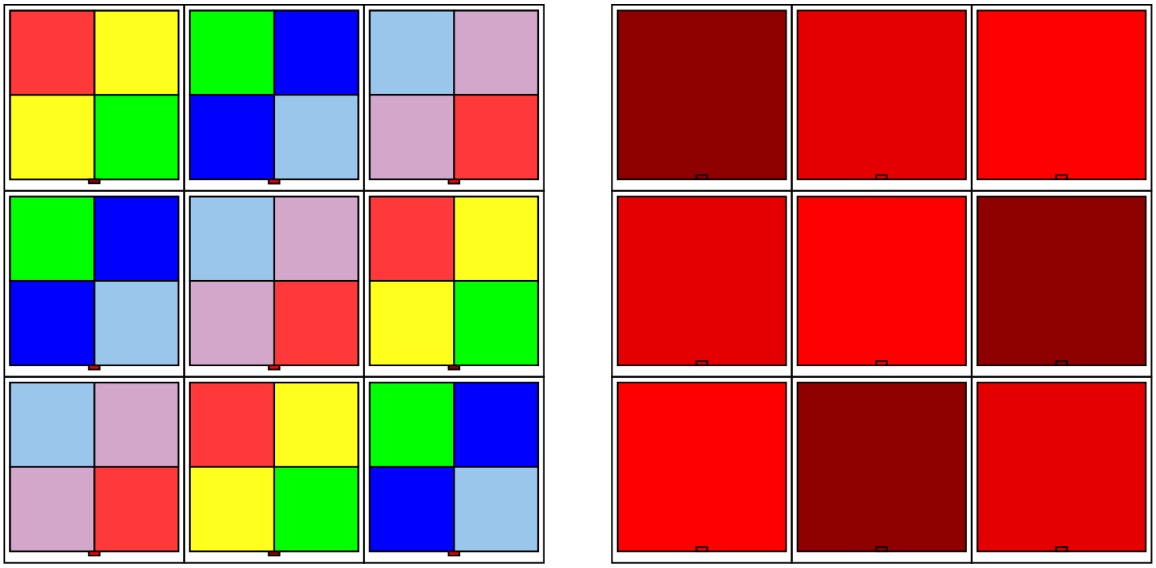


Figure 8. On the left is a two axis symmetric deployment of six filters types for the visible imager such that vertical or horizontal scan of the array through an observation field will measure all objects in all filters. On the left is the same concept for an array of three filter types for the NIR imager.

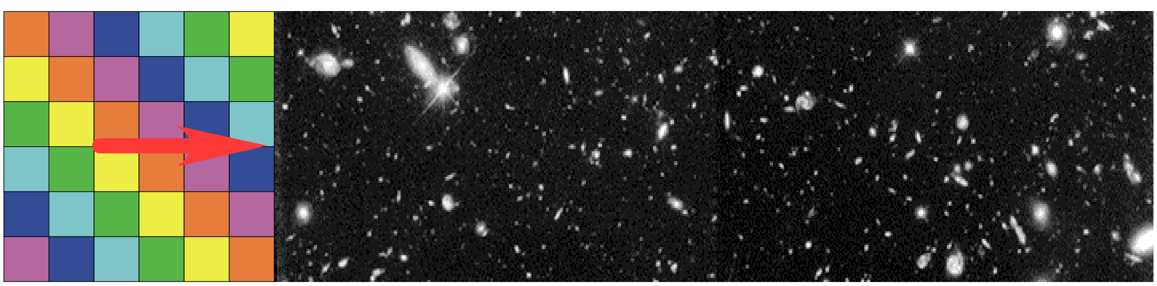


Figure 9. For any 90^{o} rotation, the filter array that is shown will allow the objects to be measured in a complete set of the six filter types.

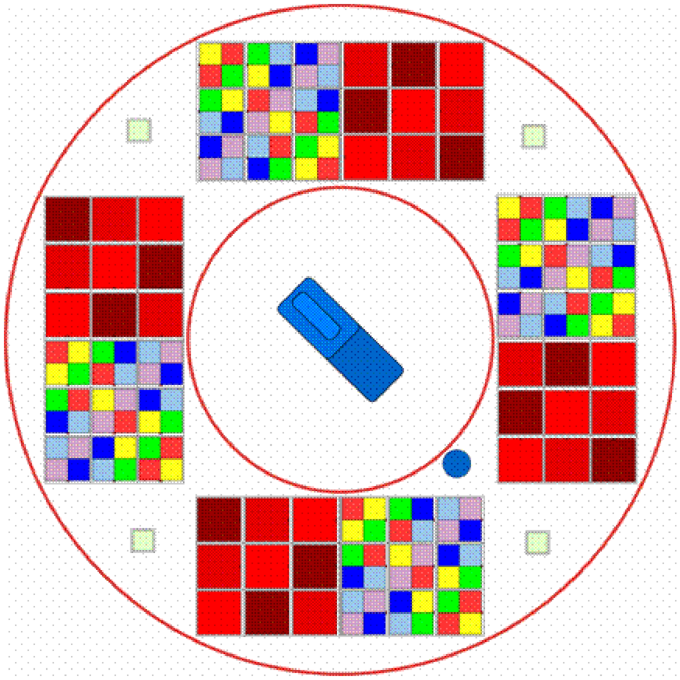


Figure 10. The SNAP working concept for the filter deployment. A two axis symmetry allows any 90^{o} rotation to scan a fixed strip of the sky and measure all objects in all nine filter types. The blue rectangle and circle are the spectrograph body and its light access port, respectively. The four small green squares are the star guider CCDs.

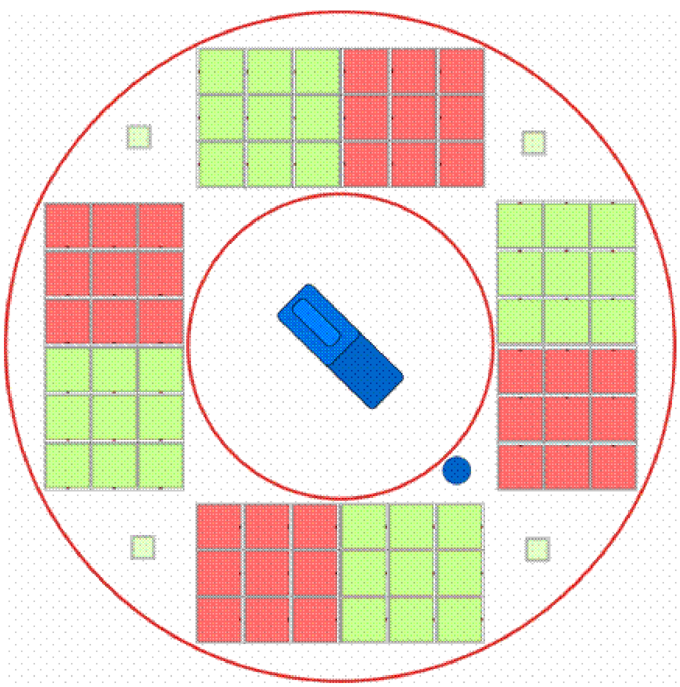


Figure 11. The underlying sensors corresponding to Figure 10. The red objects are the NIR and the green objects are the CCDs.

2.4 Near Infrared (NIR) Imaging R&D

2.4.1 Introduction

For supernovae at redshift above z =1, the cosmological redshift moves the rest-frame visible emission at ~500 nm beyond the long-wavelength cutoff of the optical CCD detectors and into the near infrared. Supernova photometry must be done at a common rest-frame (blue) wavelength if the supernovae are to be used as standard candles; hence, NIR imaging at wavelengths of 1.0–1.7 μm is a critical aspect of the mission. NIR photometry is also essential to the diagnosis and correction of systematic errors due to extinction including SNe z<1, as all known forms of dust grains give much less extinction in the NIR than in the visible. Furthermore, the NIR observations greatly expand the science reach with high statistics, high-z, wide-field measurements not accessible with any other operational or proposed instrument.

2.4.2 NIR System Baseline

The NIR system will be an integral component of the focal plane. In the baseline concept, thirty-six 2k $\times$ 2k HgCdTe imaging sensors covering a total of 0.34 square degrees will be placed in four 3 $\times$ 3 arrangements symmetric to the CCD placement. The HgCdTe devices have a cell pitch of 18 μm, resulting in a total of 150,000 pixels for the NIR system. The leading candidate for the NIR sensors is a HgCdTe focal plane array (FPA) from Rockwell Scientific (RSC). These devices exhibit low read noise and dark current while providing excellent quantum efficiency (typically 50%-80% over the wavelength interval 1.0 -1.7 μm). The largest HgCdTe devices being used by ground-based telescopes are 2048 x 2048 pixel arrays developed by RSC. Thirty-six of these devices are required for the present SNAP concept. The cutoff at a wavelength of 1.7 μm is a good match to SNAP since the sensors are blind to the thermal background radiation from the warm telescope. The Rockwell HgCdTe detector is also the leading sensor candidate for the IR spectrograph. Table 1 lists the performance specifications for the SNAP NIR system.

Table 1. SNAP NIR Performance Specifications.

Parameter	Specification	Reasoning
Field of View	~ 0.3 square degrees	match CCD FoV to observe every SN in every color
Plate Scale	0.17 arcsec / pixel	
Wavelength Coverage	1.0 µm - 1.7 µm	to observe restframe B-band out to z = 1.7
Read Noise	5 e^- (w/ multiple reads)	Assures that photometry is zodiacal light limited
Dark Current	< 0.02 e^-/pixel/sec	
Quantum Efficiency (Detector)	> 60%	to achieve adequate S/N to study SNe at z = 1.7 within time constraints
Filters	three special filters	to obtain redshifted B-band steps from 1 to 1. 7 µm

2.4.3 HgCdTe FPAs

At present there are two main technologies for large near infrared arrays, indium antimonide (InSb) and mercury cadmium telluride (HgCdTe). InSb substrate devices are under development by the ALADDIN (Advanced Large Area Detector Development in InSb) project while HgCdTe detectors are used with the HAWAII (HgCdTe Array Wide Area Infrared Imager) multiplexer, developed by Rockwell Science Center together with the University of Hawaii. HgCdTe is a ternary semiconductor compound which exhibits a wavelength cut-off proportional to the alloy composition. This allows the cut-off wavelength and thus the operating temperature, to be “tailored” to the specific application. Since the SNAP focal plane will be passively cooled to an operating temperature of 140 K the only viable technology option is HgCdTe.

The SNAP focal plane will utilize state-of-the-art HgCdTe infrared detectors. The actual detector is composed of a thin layer (10 to 20 µm) of HgCdTe with metallized contact pads defining the active area. Photons with energy greater than the semiconductor band-gap energy excite electrons into the conduction band, thereby increasing the conductivity of the material. The FPA is a hybrid consisting of a highly integrated CMOS multiplexer and an array of infrared sensitive (HgCdTe) detectors. The two pieces are indium bump- bonded together. The multiplexer is an array of discrete read-out transistors and, unlike a conventional CCD, can be read non-destructively and each pixel can be read separately and in any order.

Rockwell Science Center (RSC) is the principal, recognized source for large format HgCdTe infrared focal plane arrays and has a long history of developing devices for the astronomical community (NICMOS 256 x 256 FPAs, WFC3/HST 1k x 1k, U Hawaii, ESO, Subaru 2k x 2k).

The standard process employed by RSC to fabricate arrays is known as PACE. A layer of CdTe is deposited on sapphire substrate by chemical vapor deposition followed by a layer of HgCdTe grown by liquid phase epitaxy (LPE). Recently Rockwell has developed a process of fabricating detector layers in HgCdTe using molecular beam epitaxy (MBE). This process has been shown to result in improved quantum efficiency (QE) at short wavelengths, and is also expected to eliminate image persistence through lattice matching of the HgCdTe to the CdZnTe substrate, and reduce the intrapixel variation observed in PACE technology devices.

For SNAP we will use the currently largest available Rockwell IR device, a 2kx2k HgCdTe detector array produced in MBE technology, mated to the Hawaii-2RG CMOS multiplexer. Rockwell has developed the Hawaii-2RG (H2RG) multiplexer for the NGST project and this multiplexer is an ideal match for SNAP. The H2RG incorporates multiple output modes, operational modes and data rates. Table 2 lists the performance specifications of the concept SNAP NIR FPA. The specifications are based on the existing H2RG multiplexer hybridized to an MBE or the LPE grown HgCdTe substrate.

Table 2. The specifications for the SNAP NIR focal plane array detectors.

Parameter	Specification
Detector technology	MBE or LPE HgCdTe
Active area format	2048 x 2048 pixels
Buttability	3-side
Pixel pitch	18 μm square
Fill factor	$\geq$ 0.90
Outputs	1, 4 or 32
Power dissipation	$\leq$ 4 mW

A number of laboratories are currently engaged in characterizing the new MBE grown FPAs. The Detector Characterization Lab (DCL) at the Goddard Space Flight Center (GSFC) under the direction of Edward Cheng has been evaluating 1.7 μm H1R devices for the Wide Field Camera 3 (WFC3) project on the Hubble Space Telescope. NASA has funded four laboratories to develop and assess the quality of NGST prototype detectors; 1) the University of Hawaii Laboratory (PI Donald Hall) will develop and characterize HgCdTe detectors manufactured by Rockwell Scientific, 2) the University of Rochester Laboratory (PI William Forrest) will develop and characterize InSb detectors made by Raytheon Infrared Operations, 3) the Independent Detector Testing Laboratory (PI Don Figer) at Space Telescope Science Institute, and 4) the Johns Hopkins University will characterize both HgCdTe and InSb detectors in a comparative hardware setup.

Many of the requirements for WFC3 and NGST overlap the performance specifications for the SNAP NIR detectors and the results from these labs will be incorporated in our R&D planning. Some of the measurements that are important to SNAP are read noise, dark current, quantum efficiency (QE) and intrapixel variations. Below we list the status of these measurements.

2.4.3.1 Dark Current

Currently the performance goal on the NIR detector dark current of < 0.1 e^-/s/pix is defined by the derived NIR Imager specifications that it be less than ½ the zodiacal light. The Dark current depends sensitively on the cutoff wavelength of the HgCdTe detector and the temperature. The GSFC DLC has measured the dark current at 150 K for a sequence of 1.7 μm devices produced by RSC for WFC3. These measurements are shown in Figure 12. As RSC has gained more experience the dark current has been dropping and a number of devices have dark currents below the SNAP performance specification of 0.1 e^-/s/pix (compare production number 15, 18, 21, 25 and higher in the figure). A rule of thumb (not yet confirmed for these devices) is that the dark current should drop by a factor 6-7 for every decrease of 10 K in temperature. We are thus confident that the SNAP dark current specifications are achievable.

2.4.3.2 Quantum Efficiency

The SNAP near infrared quantum efficiency specifications of > 60% results from the need to detect Type Ia SNe at 2 magnitudes below peak luminosity out to redshifts of z = 1.7 within time constraints of the SNAP observing program. In Figure 12 it can be seen that QE has been steadily improving as RSC develops more experience with the MBE growth process. Although the QE is high in later production lots there is a significant droop at short wavelengths. RSC believes that they understand the MBE parameters that control QE and have just produced a new lot that seems to validate this claim. In Figure 13 the QE for one of these devices is uniformly high and exceeds the SNAP NIR specifications. We are thus confident that the SNAP QE solution will be inherited from the WFC3 development.

2.4.3.3 Read Noise

The SNAP specification of 5 e^-, defined by the derived NIR Imager specifications that it be less than ½ the zodiacal light, assumes that the intrinsic read noise for a single CDS read will be 10 e^- and that 4 reads at the beginning and end of an exposure will reduce this by a factor of $\sqrt{4}$. This noise performance has been achieved for all Hawaii multiplexers mated to HgCdTe material with a cut-off of

2.5 μm or greater. In principal read noise should be independent of the wavelength cut-off but this turns out not to be the case.

Recently RSC has confirmed earlier GSFC-DCL measurements of excess read noise for the WFC3 1.7 μm devices (~25 e- with a single CDS reduced to ~15 e- with 4 CDS). The cause for this behavior remains unclear. According to RSC this is a property of the 1.7 μm material, not the multiplexer, and is expected to significantly improve for devices with larger wavelength cutoff (1.9 - 2.0 μm). Current thinking attributes this excess noise to trapping centers caused by stress in the lower cut-off material.

A R&D program involving additional production runs may be needed to solve this problem. An additional run has been recommended for WFC3 and should be complete at the start of the SNAP R&D phase. If WFC3 fails to solve this problem we can explore two options. We can undergo additional production lots at RSC to continue the WFC3 development. Another option is to modify our readout strategy increasing the number of reads to achieve the required read noise.

2.4.3.4 Intrapixel Variations

Accurate photometry (~ 1% overall statistical, ~ 1% relative systematic) is the current NIR performance target until SNAP science driven requirements have been passed down to the detector level. Sensitivity variations on the scale of a single pixel can significantly reduce photometric accuracy of under-sampled images.

In the near infrared, diffraction dominates the point-spread function at all wavelengths. At 1 μm the Airy disk is Nyquist under-sampled by a factor of three for a pixel size of 18 μm. Intrapixel variations for PACE detectors has been measured by Gert Finger (ESO) and found to be quite large (see Figure 14). The fractional sensitive area ($\alpha = \int RdA/A$) for these devices has been found to be around 0.8. By controlling the growth process, MBE HgCdTe devices should have α closer to unity because the internal electric fields can be tuned to more efficiently collect the charge from the edges. The improvement in QE is a verification of this assertion. Our simulations show that dithering is required for α values below 0.98 but even for α =0.8 a simple 2×2 dither pattern with a ½ pixel dither offset can reduce this component of the photometry error to well below 1% for all wavelengths.

For MBE grown HgCdTe devices the intrapixel response has not been measured yet. The WFC3 group at GSFC has delayed those measurements due to more pressing concerns. The NGST detector lab at STScI has just initiated these measurements for 2.5 μm devices.

2.4.4 Detector Characterization and Testing

The characterization and evaluation HgCdTe detectors are a high priority for the NIR group. Our approach is to utilize existing facilities and expertise while in parallel developing the capability for detector testing and verification. The Infrared Detector Lab at the University of Michigan will provide the required environment for the comparative testing and evaluation of industry supplied HgCdTe FPAs and produce test data relevant to the success of the SNAP science program. We will measure first-order detector properties (read noise, dark current, intrapixel variation, persistence, quantum efficiency, etc.) as functions of environmental parameters (radiation exposure, thermal conditions, operating modes). The results of those measurements will allow us to specify detector characteristics which, together with the science requirements established at the beginning of the R&D program, will define the acceptance criteria for the science-grade SNAP NIR flight devices. Our plan is to concentrate on the following main issues during the R&D:

- Characterize the read noise, dark current and QE of H2RG FPAs
- Study intra-pixel variations and establish impact on accurate photometry
- Determine optimum sampling strategy for reducing RMS read-noise
- Establish facilities for receiving and qualifying NIR FPAs
- Optimize calibration techniques and strategies
- Develop a mechanical and thermal concept for NIR imager in an integrated focal plane

In order to meet the challenges and complexity associated with the NIR detector testing program, the Michigan IR laboratory will consist of three functional sections with the following responsibilities:

Detector Systems: This encompasses all activities related to detector characterization and testing and also includes the optimization of detector performance and detector data analysis methodologies.

Software Development: The acquired data acquisition system from ARC only provides basic control and read modes. Additional functionality has to be programmed. Image analysis software and data analysis software has to be written. Software is also needed to support detector data archiving and detector data base management. All software needs to be maintained.

Laboratory Systems: A laboratory conditions data acquisition system has to be created. These data have to be archived in order to provide environment tractability for each experiment.

There will be a cost and schedule risk associated with the procurement of several dozen science grade 2k x 2k HgCdTe CCDs during phase B. Our R&D plan is focused on mitigation of this risk through early procurement and test of several

HgCdTe devices from Rockwell in phase A: A fully functional device (“science grade”) will be acquired at the beginning of FY03. This device will allow us to measure and verify the vendor specified properties and to establish the SNAP science grade definition. We will then acquire two SNAP science grade devices in FY04.

Rockwell has set up a new $25M facility dedicated to HgCdTe device fabrication, and this has greatly expanded their production capability. This is a new facility, however, and it is important to carry out a program of measurements to establish whether the Rockwell devices meet SNAP requirements for IR imaging and IR spectroscopy. We will work closely with the vendor to develop a plan for device qualification and acceptance. We note that other projects also plan on extensive NIR imaging capability, for example the WFC3 on HST and the NGST, and we will consult extensively with their design groups to take advantage of their development efforts.

2.4.5 Progress in the Past Year

Our focus during the past year has been on the design of an optimal selection of detectors and detector arrangement for the focal plane that will maximize the science return while minimizing technical risk. Through numerous discussions with Rockwell Science Center and with the Detector Characterization Lab (DCL) at Goddard Space Flight Center we have developed a baseline detector concept and decided on a hybridized Hawaii-2RG as the SNAP NIR FPA.

We have designed and ordered an infrared camera dewar and read-out electronics from Astronomical Research Cameras (ARC). The dewar setup has been customized for the H2RG multiplexer but initially we will test the available Hawaii-1 RG multiplexer (Figure 15) which is accommodated through mounting on a Hawaii-2 RG carrier. This will give us the immediate capability of debugging and optimizing the test set-up and also will allow us to conduct first measurements. When the 2-RG device becomes available we will be able to use the same dewar and mechanical mounting system and the same electronics for testing. A device for producing sub-pixel size NIR spots (`Spot-O-Matic') to study intra-pixel variations has been designed.

We have begun initial setup of the Michigan IR Detector Lab. This facility will be a class 100,000 clean room with continuous purge of the test room with filtered air and with an adjacent separate computer control room. The following equipment has been acquired:

- IR Dewar
- LN2 fill-up system
- Data acquisition and control computer
- Uninterruptible Power Supply (UPS) for computers and critical hardware
- Optical bench

The optical system for subpixel illumination is under development.

2.4.6 NIR Imaging R&D plan

The primary R&D goal is to refine our requirements for the wide-field NIR imager based on additional mission simulations and hands-on experience with HgCdTe devices. This will conclude in the NIR systems requirements specification document at the end of the R&D phase. An important element of this task is to develop detailed acceptance criteria and qualification procedures for the HgCdTe devices in coordination with the vendor. The mechanical and thermal design for the NIR and optical imagers are closely coupled in the integrated focal plane concept and will be developed jointly with LBNL.

The main NIR system R&D activities are:

- To establish a facility for testing and characterizing NIR FPAs at the University of Michigan.
- To study the detector read noise and the ability to reduce it with multiple reads.
- To study the intrapixel variations and establish the impact on accurate photometry.
- To develop the mechanical and thermal concept for NIR imager in an integrated focal plane.
- To develop the plan for testing and qualifying a large number of HgCdTE devices.
- To produce the R&D phase deliverables.
- To produce realistic cost and schedule estimate for CDR.

2.4.6.1 Conceptual design development

Now that our initial trade studies are complete, we will develop our working model into a full conceptual design. This design work will begin by establishing a detailed and refined set of requirements. With requirements in place, we will begin parallel development of the optical, mechanical, electronic, computing, and thermal designs. The integrated focal plane concept necessitates a common approach for the optical and NIR sensors to these topics, so teams will work in close communication with each other and with the other SNAP design groups. There will be substantial overlap between these activities.

2.4.6.2 Develop baseline optical design

There are several options for fixed filters that we plan to evaluate. The fixed filters may be mounted just above the sensors, glued directly to the sensors, or grown on the sensors as part of the sensor processing. Filter materials will be selected and filter performance specifications will be established. This work will be done in cooperation with the work on filters for the silicon CCDs.

2.4.6.3 Develop baseline electronics and control design

The design of the readout electronics for the NIR system will make use of the electronics developed for the SNAP optical imager. Supplementary electronics for the NIR system will be defined at a level sufficient for establishing power, weight, cooling design and cost.

The SNAP orbit will be outside the Earth's radiation belts and only solar flares and cosmic radiation might affect the detector and electronic components. We will evaluate the impact of such radiation and the electronics design will include radiation-hardness considerations.

2.4.6.4 Develop Mechanical and Thermal Design Specifications

The NIR array will be integrated along with the CCDs to produce the complete SNAP focal plane imaging system. This system will be passively maintained at a temperature of 140 K. As part of the R&D effort, we will work closely with the CCD and engineering groups at LBL to produce an overall focal plane mechanical and thermal design which ensures the proper performance of the NIR camera. Issues to be addressed include:

- Thermal coupling (both radiative and conductive) of the HgCdTe devices to the focal plane substrate and surrounding instrument to minimize temperature gradients across individual devices, as well as the total array, in order to minimize intra-pixel differences in quantum efficiency, dark current, and noise.

- Mechanical mounting which minimizes residual stress on the devices, maintains accurate spatial alignment of the devices within the array, adequately isolates the devices from launch vibration, and minimizes thermal stress on the devices during initial cool-down on orbit.

2.4.6.5 Characterize HgCdTe devices

In order to gain experience with HgCdTe devices and to perform tests and measurements, we have begun to set up an infrared detector laboratory at the University of Michigan. Our priority was to acquire a chip with the new performance-enhanced CMOS readout (RG). We have obtained a H1RG (1k x 1k) multiplexer and will obtain a science grade H2RG device in FY 03.

We will learn how to operate the HgCdTe device to achieve the required dark current level (for both imaging and spectroscopy) and to minimize internal glow. We will use it to establish the optimal operating temperature that will maximize the quantum efficiency while minimizing read-out noise. We will characterize spurious read noise due to trapped charges and establish an optimal reset scheme. We will experiment with schemes for vetoing cosmic rays through “up the ramp” sampling and fitting. We will also study intra-pixel variations and calibration techniques. We will develop and bench test our thermal and mechanical design as well as computer control and read-out.
The construction of the test set-up and the experience we will gain will enable us to receive and qualify FPAs for the SNAP mission (both imaging and spectroscopy).

2.4.7 CDR planning

The deliverable at the end of the R&D phase is a cost and schedule estimate for construction of the NIR imaging system. Assembly of a NIR camera test system will be essential in establishing that requirements are met and in firming up cost estimates. It is likely that much of the work for the NIR optical and mechanical systems will be done in parallel with the primary optical and mechanical assemblies.

2.4.8 R&D deliverables

Table 3 lists deliverables generated during the R&D effort.

Table 3. NIR system deliverable dates.

Deliverable	Date
Draft NIR system science requirements	Aug 2003
NIR system mechanical and thermal specifications document	Jan 2004
Plan for receiving and qualifying flight detectors	May 2004
Integration and Test Plan.	May 2004
NIR system interface control document.	May 2004
NIR observation plan.	Jun 2004
Science grade HgCdTe detector meeting all NIR science driven requirements.	Jun 2004
SNAP HgCdTe FPA science grade specifications	Jul 2004
WBS, cost, schedule, management, risk management and de-scope plan for design, construction and operations phases.	Jul 2004

2.4.9 R&D milestones

Table 4 lists milestones

Table 4. NIR system milestones.

Milestone	Date
HgCdTe evaluation facility debugged and operational	Dec 2002
Noise measurements on H1RG multiplexer	Feb 2003
SNAP internal IR detector review	Feb 2003
Noise and intrapixel measurements on science grade H2RG detector	Jul 2003
NIR Draft Requirements Review	Aug 2003
Preliminary “SNAP” HgCdTe science grade specifications	Sep 2003
Noise and intrapixel measurements on “SNAP” prototype science grade H2RG detector	Jan 2004
Prototype demonstration: HgCdTe + readout	May 2004

2.4.10 Risk assessment and risk mitigation

The production and availability of the desired 1.7 μm cut-off FPA device depends on the commercial vendor (Rockwell). Limited space experience with HgCdTe devices exists. We will mitigate this risk by extensively testing the HgCdTe devices and sharing information with the NGST and HST IR detector groups.

The SNAP NIR system will have the largest number of infrared detectors ever and thus presents unique challenges. HgCdTe focal plane arrays are a relatively new but rapidly developing technology. R&D phase will be used to mitigate risks in key detector technology areas such as noise, intrapixel variation and qualification testing. We intend to mitigate these risks by extensively testing the HgCdTe devices and by working closely with the NGST and HST IR detector groups.

2.4.10.1 Read Noise

A program involving additional production runs may be needed to solve the problem of excess read noise. An additional run has been recommended for WFC3 and should be complete at the start of the SNAP R&D phase. If WFC3 fails to solve this problem we can explore two options. We can undergo additional production lots at RSC to continue the WFC3 development. Another option is to modify our readout strategy increasing the number of reads to achieve the required read noise. We will measure the read noise of our science grade devices and characterize its dependence on temperature. We will also explore the trade off of read noise, dark current and cut-off wavelength. We will test various read-out strategies to define the optimal SNAP science grade HgCdTe specifications that will meet the SNAP science driven requirements.

2.4.10.2 Intrapixel Variation

The intrapixel response may be acceptable as it is or it may not be. If not, RSC can work on improving the deposition process to “sculpt” the electric field so as to more efficiently collect the charges near the pixel edges. We fully expect that simple dithering will be the solution to photometry errors introduced by intrapixel variations. We intend to demonstrate that this is the case by measuring the sub-pixel response and by laboratory verification of the dithering strategy.

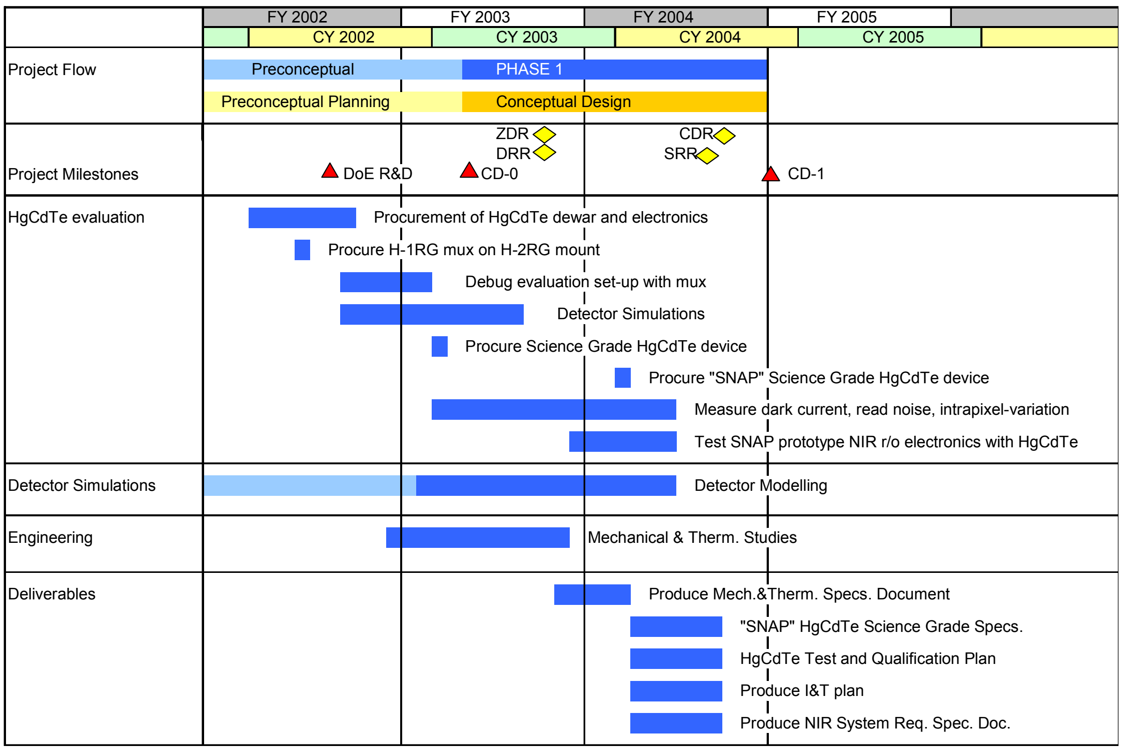
2.4.10.3 Qualification Testing

As part of our R&D program we need to define a program for the characterization and qualification of a large number of HgCdTe devices. To obtain 44 science grade devices (36 flight, 8 spare) we will need to test at least several hundred devices. In comparison, NGST intends to obtain 25 science grade devices (20 flight, 5 spare) and are planning to utilize three large facilities for this effort. Our plan is to develop a prototype SNAP NIR FPA characterization facility at Michigan, based on experience gained from existing facilities that will serve as a model for large scale detector qualification in phase B.

2.5 Schedule

The schedule shown in Table 5 tracks the narrative.

Table 5. NIR development schedule summary.



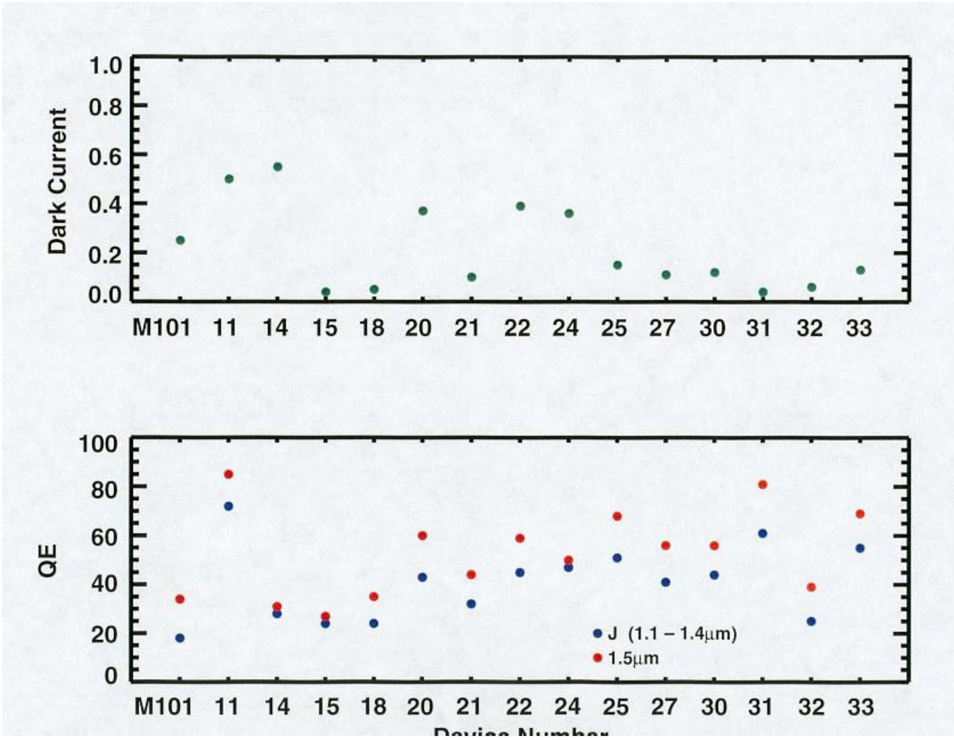


Figure 12. Measurements made at DCL (Goddard) on Hawaii-1R with λ_c = 1.7 μm at 150 K (courtesy of B. Hill).

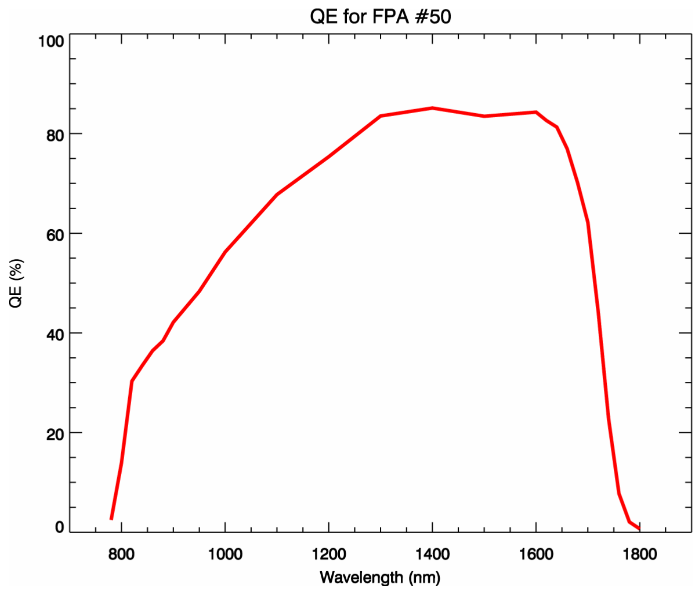


Figure 13. Quantum Efficiency vs. wavelength for one HgCdTe device in the most recent production lot produced by RSC for WFC3 and measured by Gert Finger (ESO).

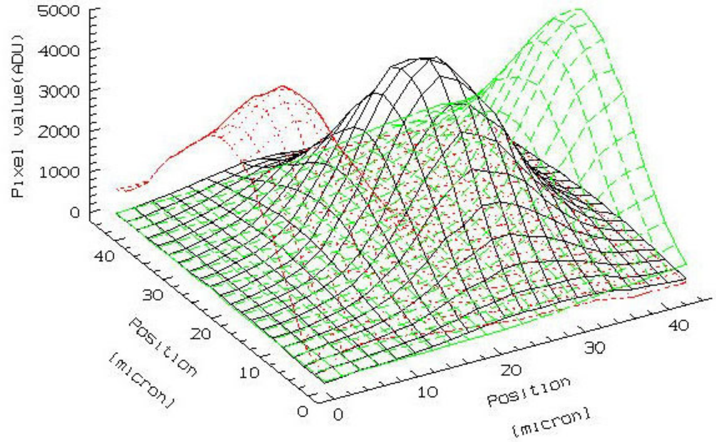


Figure 14. Intrapixel sensitivity of PACE HgCdTe as measured by Gert Finger (α=0.8).

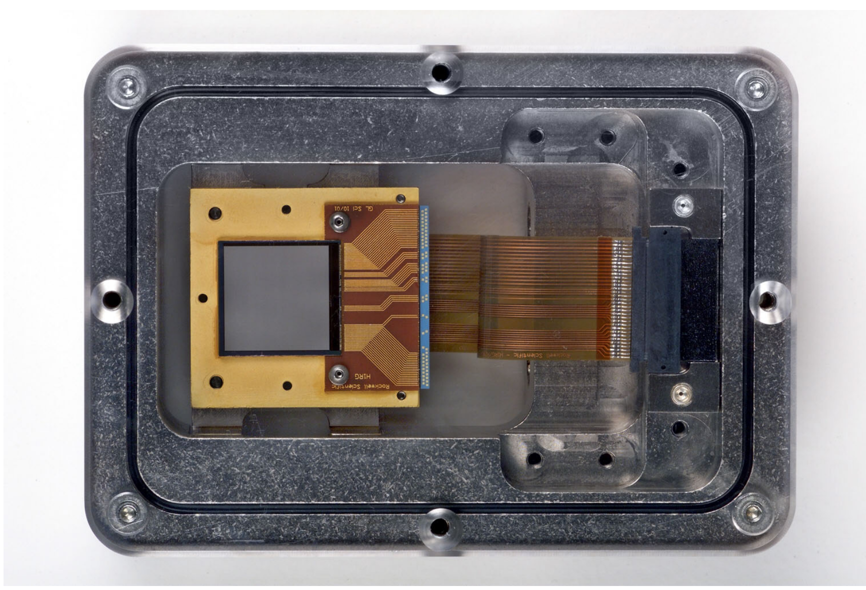


Figure 15. Rockwell H1-RG multiplexer on an H2-RG mount.

2.6 CCD R&D

2.6.1 Introduction

LBNL has developed a new type of CCD based on n-type high-resistivity silicon with p-channels. The back-illuminated CCDs are 200-300 μm thick and the substrate is fully depleted by the application of an independent voltage through an optically transparent backside contact. The extended red response and the increased radiation tolerance compared to conventional n-channel CCDs make these devices the suitable for SNAP.

The NOAO September 2001 newsletter cover featured an image of the Dumbbell Nebula NGC 6853 acquired with one of our 2k x 2k CCDs taken at WIYN 3 m (Figure 16). All three false colors made use of the extended red response of the CCD. Other activities at NOAO involving the use of our CCDs are: a supernova spectrum taken by the LBNL Supernova Cosmology Project (Figure 17) on the RC Spectrograph; instrumenting the Multi-Aperture Red Spectrometer (MARS) with one of our CCDs for scheduled public use for 37 nights from January to July 2002; and discussion about providing four 2k x 2k devices for a new focal plane mosaic. A CCD is also in use on the Lick 3 m Coude Eschelle Spectrograph.

The additional research efforts on the LBNL CCDs are completion of measurements of imaging performance and radiation tests with cold, powered device. The additional development efforts concentrate on device fabrication and design perturbations to insure good spatial resolution and long term operation with substrate voltages approaching 100 V.

2.6.2 LBNL CCD technology

Figure 18 compares a conventional back-illuminated CCD with the LBNL technology. LBNL CCDs are fabricated on float-zone refined high-resistivity (~10 kΩ-cm) n-type silicon. Holes, rather than electrons, are collected in the potential wells. An indium-tin oxide coating on the back surface provides three functions:

1. A contact for a bias voltage that completely depletes the substrate so that photo-generated charge from the whole volume is collected.
2. A transparent window, permitting back illumination.
3. Part of the back-surface anti-reflective (AR) coating.

Since the devices are thick, they exhibit excellent quantum efficiency in the red until just below the silicon bandgap at 1050 nm, and at the same time interference fringing is completely absent.

Since blue light is strongly absorbed in the gate structure of any front-illuminated CCD, the CCDs used in astronomy are usually thinned and back-illuminated. For most devices (~20 μm thick 10–50 Ω–cm epitaxial layer), this means thinning to about 20 μm. The thinning results in transparency in the red, resulting in a loss of quantum efficiency (QE) and fringing due to multiple reflections. For the LBNL devices this aggressive thinning process is both unnecessary and undesirable.

Advantages of the novel LBNL CCDs include:

1. High quantum efficiency (QE) up to wavelengths approaching the silicon bandgap at just above 1050 nm, where silicon becomes transparent.
2. Absence of fringing. The interference patterns that are present in thinned spectroscopic CCDs are completely absent in these thick devices.
3. Good blue response without special processing and without UV flooding. A normal CCD exhibits field inversion near the back surface, resulting in the loss of QE for blue light where the absorption length is very short. Since holes, rather than electrons, are collected in the CCDs, the problem does not exist and the fully-depleted substrate has no field-free region.
4. The very low concentrations of phosphorus and oxygen in the n-type high-resistivity device result in excellent radiation tolerance.
5. Large well-depth of 300,000 e^- for 15 μm pixels and 130,000 e^- for 10.5 μm pixels.
6. Low noise readout.
7. Capitalizing on the device thickness, the CCDs can be readily packaged for four-side abutment with standard wire-bonding techniques enabling the manufacture of very large mosaic arrays.

The commercialization of this technology is well underway. CCDs have been successfully fabricated by DALSA on 100 mm and 150 mm wafers but this is not yet fully industrialized. We will be exploring several fabrication scenarios that are consistent with the quantities and timescale required by SNAP,

2.6.3 CCD testing status

To support the testing of CCDs we have in use three sets of dewars, Astronomical Research readout controllers, and SUN workstations. We have an ever growing suite of software for the readout controllers and the workstations to support new measurement procedures.

2.6.3.1 <u>General CCD performance parameters</u>

We have tested a range of CCD architectures with pixel sizes of 10.5, 12, and 15 μm and pixel counts up to 4800 x 1800. In Table 6 we show routinely achieved results for a variety of CCD characterization parameters. A measurement of backside illuminated quantum efficiency is shown in Figure 19. The broad spectral sensitivity is readily apparent.

Table 6. LBNL CCD characteristics.

Parameter	**Typical value**
Dark current	0.001 e/s/pixel @ 140 K
Read noise	2 e @ 50 kHz; 3 e @ 100 kHz
Sensitivity	3.5 μV/e
Well depth	300 ke for 15 μm 130 ke for 10.5 μm
Charge transfer inefficiency	2×10^{-6} @ 140K

These CCDs do not have provision for anti-blooming; bright objects that saturate the well depth can result in persistent images after readout. An erase mechanism is provided to neutralize trapped surface charge. We find that saturated regions achieve the low dark current of an unexposed region after an erase cycle.

2.6.3.2 Operating characteristics

We have made an extensive study of the temperature (100–300 K) and substrate voltage (25–75 V) dependence of the output MOSFET. Figure 20 shows the subthreshold dependence on substrate voltage at fixed temperature and Figure 21 shows the subthreshold dependence on temperature. The subthreshold substrate voltage and temperature dependence are not unforeseen; the results simply help to establish the proper operating conditions for a CCD at a given temperature. Figure 22 shows a family of I-V curves at 150 K where the substrate voltage is varied. Figure 23 shows transistor gain g_m dependence on substrate voltage at fixed temperature. While there is too much data to present here, two observation can be made: the substrate voltage should be 45 V or greater and g_m continues to increase down to 120 K.

We have also been studying the noise performance of our output MOSFETs to understand the limits achievable on readnoise versus read rate and to look for areas of further improvement. Figure 24 is a plot of the noise spectral density for one of our output transistor structures. An expected region of 1/f falloff is seen and the white noise floor (15-20 nV/rt-Hz) is also evident. After signal processing, it is this latter value that is most important.

2.6.3.3 Radiation performance

Historically, CCDs have been very sensitive to non-ionizing radiation such as low energy protons encountered in space. We have so far studied the degradation of the LBNL technology with 12 MeV protons at the LBNL 88” Cyclotron. As in any CMOS structure, CCDs are sensitive to charge accumulation in and at oxide interfaces. We have measured this with ^{60}Co exposures at the LBNL source. The LBNL CCD technology has a large charge sensitive volume. A side effect is a larger cross section for background particles such as Compton electrons from normal environmental materials. We have examined the radiological purity of the potential CCD packaging materials in the LBNL Low Background Facility.

Protons

Proton irradiation generates displacement damage in the silicon. Midgap levels in the depletion region will contribute to the dark current. Traps in the channel region capture charge carriers during readout and degrade the charge transfer efficiency (CTE). We studied two sets of four CCDs that were characterized and then irradiated with 12 MeV protons at the LBNL 88" Cyclotron. We used our commercially fabricated 512 x 1024, 15 μm pitch CCDs as front-illuminated devices. The four CCDs from each set were irradiated at doses of 5×10^9, 1×10^{10}, 5×10^{10}, and 1×10^{11} protons/cm^2. The irradiation took place while the devices were unpowered and at room temperature. After irradiation the devices were again characterized to evaluate the performance degradation due to radiation damage.

CTE was measured as a function of temperature with a 30 kpixel/sec readout rate and an x-ray density of roughly 1/70 per pixel. The pre-irradiation CTE of the devices was 0.999999. Figure 25 shows the parallel and serial CTE as a function of radiation dose at 128 K. In Figure 26 we compare the CTE damage rate of our CCDs with two commercial devices that have been measured in a similar way.[1,2] Our damage rate is 8 to 10 times lower than these devices.

Because of its use in high energy physics experiments, radiation damage in silicon particle detectors has been studied extensively. As a result of the fabrication process, carbon and oxygen are the common impurities in high-resistivity n-type silicon.

The radiation induced interstitial carbon trap C_i is most likely produced via the following mechanism: proton collisions create an interstitial S_i atom which then

[1] L. Cawley, C. Hanley, *WFC3 Detector Characterization Report#1: CCD44 Radiation Test Result,* Space Telescope Science Institute Instrument Science Report WFC3 2000-05, Oct. 2000.

[2] T. Hardy, R. Murowinski, and M.J. Deen, “*Charge transfer efficiency in proton damaged CCD's,"* IEEE Trans. Nucl. Sci., 45(2), pp. 154-163, April 1998.

replaces a substitutional carbon C_s in the lattice. The resulting C_i is not stable but decays eventually to a C_iO_i or a C_iC_s trap. The decay rate at room temperature depends strongly on the C and O concentrations but generally requires a few days. The C_iC_s hole trap has a very low energy (~0.08 eV) and should not contribute to the CTE over our temperature range. The C_iO_i trap, however, is a candidate for CTE degradation.

Vacancies produced by proton irradiation migrate around the lattice until they form pairs with other impurities or with other vacancies. Most stable of these are the divacancy VV and the VO electron trap. The VV trap is considered to be the dominant hole trap expected in irradiated p-channel CCDs.

We have used our parallel and serial CTI measurements at different temperatures and different radiation doses to identify the degradation mechanism. A three-trap model has been developed that has only the three trap densities as free parameters. Typical measurements and fits are shown in Figure 27. The fitted trap concentrations are shown in
Figure 28. We have found no evidence for pure C_i traps; they have transitioned to C_iO_i traps.

Since our CCDs have a much larger depleted volume than conventional CCDs, the concern existed that unacceptable dark current levels might result from radiation damage. Figure 29 shows the measured increase of dark current with radiation dose at one fixed temperature. The increased dark current is modest.

For reference, the expected SNAP mission dose for CCDs behind appropriate shielding will be $<10^{10}$ p/cm^2 or $<5\times10^7$ MeV/cm^2 in Figure 25, Figure 26, Figure 28, and Figure 29.

<u>^{60}Co</u>

P-channel CCD transistor and MOS capacitor test devices have been irradiated with ^{60}Co to doses of 5 and 20 krad in order to study the effects of ionizing radiation on our commercially-fabricated p-channel CCDs. The main concerns for ionizing radiation are charge trapping and interface-state generation in the device insulators resulting in threshold shifts and increased dark current. For these initial tests, two die were irradiated but it was not possible to bias the transistors and capacitors during the irradiation. Since the technology is p-channel, the usual problems with field threshold voltage lowering are not expected. The main concerns are transistor threshold voltage (V_T) shifts, mobility reduction, and dark current increase due to surface state generation.

Figure 30 shows output characteristics of a 51/5 buried channel p-channel MOSFET. The large V_T shift with drain voltage (drain-induced barrier lowering) is typical of devices fabricated on high-resistivity silicon. Figure 31 shows subthreshold characteristics measured on field oxide transistors. Subthreshold slope degradation is starting to become noticeable at the highest ^{60}Co dose. In any event, the magnitude of the field V_T increases with dose, implying better isolation with increasing ionizing dose.

None of the results are out of the ordinary. For space use, if the dose is large, modest adjustments of clock and transistor biases, up to 1 V after 20 krad, will restore initial operating characteristics.

Background radiation

Our CCDs are up to ten times thicker than conventional CCDs. This larger volume increases the number of pixels impacted by cosmic rays and background radiation. Figure 32 shows a 1000 s dark exposure. The straight lines are cosmic rays and the others have been identified as Compton electrons from normal background radiation. Besides natural backgrounds, the materials that are used to package CCDs can be a source of excess pixel hits. Various materials have been studied to identify those that are clean. We have made use of the LBNL Low Background Radiation Facility to identify suitable materials. Good materials identified so far are pure metals, Kapton, aluminum-nitride, printed-circuit boards without flame retardant.

2.6.4 CCD testing plan

There are a few remaining areas of CCD performance that need to be measured; cross talk, diffusion, and intra-pixel response. There are also two areas related to space operation that need to be brought to closure: long term operation with substrate voltages between 80 and 100 V and radiation testing with cold, powered devices and characterized without warm-up. We will need to liaise with the readout ASIC development to interface first with the CDS and later with the combined CDS/ADC. Our commercial readout system will continue to provide clocking and bias voltage generation during readout of actual CCDs. To summarize, the planned testing activities are:

- Measure cross talk
- Measure charge diffusion
- Measure Intrapixel response
- Study operational issues with large substrate voltages
- Perform cold, powered proton irradiation
- Perform cold, powered ^{60}Co irradiation
- Study and possibly test heavy ion radiation
- Interface CCDs to prototype readout ASICs

A continued level of effort for routine testing of new CCD layouts and process variations will be needed. This is coupled with the CCD fabrication development plan discussed below. Also, we intend to package a modest number of devices for ground-based use. This will require the development of routine test and qualification procedures. This is relevant to SNAP in that more pre-flight operational experience will be obtained and an assembly and testing model for SNAP CCD production can be extracted. Furthermore, we intend to package and test actual SNAP format devices. To this end, we are setting up a test facility adjacent to the assembly cleanroom that is separate from the existing CCD test lab.

2.6.4.1 Cross talk

To meet the readout time specification of the SNAP imager, CCDs with four to eight taps will be required. This introduces the possibility of a bright pixel being read at one tap introducing ghost images in the other taps. The steerable pinhole projector we have developed for diffusion and intra-pixel response studies is ideal for studying this. We have existing CCDs with two and four taps that can be used.

2.6.4.2 Charge diffusion

An important program for the next year is to understand charge diffusion for backside illuminated devices. For our thick devices, diffusion is a function of the thickness, wavelength, and depletion voltage. Short wavelength photons convert at the backside of the CCD and the resultant holes drift to the collection well in an electric field generated by the depletion voltage. A hole never sees a field free region and thus has a well defined drift time through the device. During the drift, there will be lateral diffusion which will increase the point spread function. We have two handles on diffusion, the CCD thickness and the depletion voltage. The diffusion is linear in the former and goes as the inverse square root of the latter. For our technology, a 200 μm thick device depleted at 60 V should have an rms diffusion constant of 4 μm, a good match for a 10.5 μm pixel and the diffraction scale of point objects in SNAP.

We have constructed a pinhole projector with a 2.4 μm FHWM beam that can measure diffusion at this level (Figure 33). Measurements are just beginning.

2.6.4.3 Intrapixel response

Once charge has drifted to the collection region, it should be captured in the appropriate pixel without further distortion due to irregularities in the termination of the drift field. Detailed electrostatic simulations indicate that this should not be a problem. A pinhole much smaller than the pixel size can be scanned across the backside in submicron steps and distribution of the collected charge analyzed. Again, our new pinhole projector will be used for this.

2.6.4.4 High voltage testing

We routinely operate CCDs with depletion voltages of 80V and do not observe breakdown. A review of the CCD design indicates that internal fields can be reduced by a factor of three by using a thinner field oxide and a lower channel stop implant dosage. A repositioning of the ground guard ring can further isolate the substrate power supply from the channel region. We have a few test CCDs with the modified guard ring in hand and are testing them. New CCDs from an existing mask set will explore the field oxide and implant dosage reduction of breakdown voltage.

2.6.4.5 Radiation

The planned radiation tests are for cold, powered devices. We believe that our room temperature study of proton generated traps is sufficient to predict the cold temperature results but the measurements will be done anyway. This will entail measuring CTE and dark current at 140 K for a few radiation dose levels. Ionizing radiation at cold temperatures can integrate trapped charge in oxide layers more quickly than at room temperature due to different annealing times. We will measure cold, powered devices at the LBNL ^{60}Co source. We will look for CTE changes and operating voltage offsets for a few dose levels.

We are working to understand the flux and probable energy deposition of highly ionizing heavy cosmic rays in shielded CCDs. The concern is the whether enough localized ionization can occur to cause a fatal discharge of the substrate voltage across a CCD insulating layer. If concerns remain after the study, we will have to perform exposures either using the “cocktail” beam at the LBNL 88” Cyclotron or at BNL.

2.6.4.6 ASIC development support

The development of an integrate circuit for processing the CCD analog signals has two scheduled tests of prototypes attached to a CCD. The first test has only the correlated double sample which needs to be interfaced to the clock and bias generators of our test lab controllers. The second test provides a correlated double sampler and an ADC. Again, a test lab controller will provide clocking, bias generating, and data collection.

2.6.5 CCD packaging status

Before a CCD can be tested, it needs to be packaged so that thermal and electrical contact can be made. We have mostly been doing packaging in a conventional lab environment. This has been adequate for the electrical measurements but we need to take greater cautions as optical measurements become more important. Also, to measure the yield of CCD production we need to implement strict ESD protection procedures. We have constructed a Class 10000 clean room for assembling the CCDs onto their mounts. Supporting equipment installed are a refrigerator for glue storage, a vacuum oven, a laminar flow bench, and a wire-bonder. We are setting up a test and measurement facility adjacent to the cleanroom that is dedicated to production of devices for distribution to ground based telescopes and for SNAP preproduction.

We have developed a concept for packaging CCDs into modules that can populate a focal plane mosaic. The concept is illustrated in Figure 34. A CCD is glued to a thick AlN substrate that is patterned with electrical traces and contracts. Wire-bonds provide contact between the substrate and the CCD. This is then glued to a molybdenum mounting block containing precision alignment pins. Precise control of the stacked height of the assembly is provided by glue layers and precision gluing fixture shown in Figure 35.

Materials measurements — radiological, chemical, and mechanical — have been done to ensure compatibility with the silicon of the CCDs. The optical prescription of the telescope is being used to develop mechanical placement tolerances for the packaged CCD modules. Control of the SNAP focal plane surface to ±20 μm appears to be achievable since we are obtaining package height control of 5 μm at room temperature.

Figure 36 shows a schematic stacking of materials for a CCD mount. We make use of the LBNL speckle interferometer to measure surface deformation from room temperature to 120 K. Figure 37 is an interferograph of the CCD optical surface at 140 K. The peak to valley variation is about 6 μm.

2.6.6 CCD packaging development plan

The CCD packaging efforts described above immediately address delivery of large format devices for ground-based astronomical use. Obviously, this is of direct benefit to the development of the packaging for SNAP. To support the packaging effort, a shop foreman and a technician will be hired over then next 15 months. From this small production packaging facility we will develop procedures and yields for production of SNAP parts. SNAP prototype CCDs are expected to be available in mid-FY03.

Two refinements of the existing packaging concept will be explored. We are exploring the use of a silicon substrate instead of AlN so as to completely eliminate stress in the CCD front-side surface due to differential thermal contraction between room temperature and 140 K. In the long run, it is desirable to eliminate the wire-bonds and provide full area support to the CCD. Recent work by others in this area will be explored.

2.6.7 CCD production status

We have fabricated 10.5, 12, and 15 μm CCDs devices in a variety of formats up to 2k x 4k on 100 mm wafers at MSL (LBNL Micro Systems Lab) and commercially and on 150 mm commercially. These have ranged from 190 to 300 μm thick and some of these devices are deployed in ground-based telescopes as mentioned above.

We have been working with DALSA Corporation over the last three years, transferring our process technology. Devices up 2k x 2k with 15 μm pixels have been successfully built and devices as thin as 200 μm have been finished. DALSA has converted exclusively to 150 mm wafers. These wafers are must be thinned from ~675 μm to 200–300 μm for our use. This new complication is discussed below. To verify the 150 mm production line we have been fabricated unthinned photodiode wafers with good results. Figure 38 shows a photodiode wafer. A few thinned wafers have been fabricated and we found similar backside damage areas that we have already eliminated at LBNL. This will discussed below. Unthinned CCD wafers have been fabricated that were of high quality in front illuminated studies. Figure 39 shows a 150 mm wafer fabricated at DALSA containing a variety of CCDs and Figure 40 shows a front-illuminated image from a 2k x 4k device. We have received one thinned (300 μm) CCD wafer from DALSA that is now under backside illumination tests. Figure 41 shows some backside images from one device. We believe this to be the world's first commercially fabricated p-channel, fully-depleted, back-illuminated CCD.

In the last year, much LBNL effort has gone into developing careful handling procedures and equipment modifications to protect the backside of the wafer during manufacture. Backside scratches through the ISPD (in situ polysiicon deposition) layer are fatal for fully-depleted operation. To first order, our experience is that the main culprit is particles and that they can be removed with mechanical action (scrubbing). Again, the main concern is damage to the thin backside poly layer. Procedures we have learned are

- Use of sacrificial SiO_2 layer on wafer backside. This is not scratch immune but allows for undercut of particles during strip.
- Particle removal via wafer scrubbing is the most effective technique to date.
- Use of wear resistant materials on vacuum chucks and wafer handlers where possible (DuPont VESPEL® is effective but does shed particles).
- Avoid use of silicone parts. Particles deposited by these cannot be remove with scrubbing.
- First wafers through equipment (coater, aligner) tend to have significantly higher particle counts.
- Photoresist aerosol particles are too large to be removed with plasma ashing and require the addition of a solvent to the scrubbing soap solution.

We are gradually transferring our backside handling knowledge to DALSA but expect this to take some time to fully implement. We view this as the second phase of our commercialization effort. We use our photodiode wafers to develop the backside technology with DALSA since the simple mapping out of the dark current across wafer as a function of depletion voltage monitors the backside quality. The first back-illuminated 360 μm thick wafers showed excellent dark current below full depletion but poor yield above full depletion; there was much visible damage on back side of wafer. After transferring our backside processing remedies to DALSA, 300 μm thick wafers showed excellent dark current below full depletion, ~10% bad pixels at full depletion, and much less visible damage on back side of wafer. In producing these wafers, the issue of breakage while processing thinned wafers on automated equipment designed for normal thickness wafer production arose. This was not unanticipated.

We moved on to having DALSA fabricate one lot of 150 mm CCD wafers. The unthinned wafers had excellent performance for front-illuminated devices, so process flow appears stable. The problems discussed for thinned photodiode wafers were also present when thin wafers were processed: damage to thin backside poly layer during processing and breakage of 300 μm thick wafers. One wafer did make it as far as the LBNL AR coating step where it broke but some CCDs were salvaged for testing.

Understanding that it is going to take time for DALSA to learn to process thin wafers on their automated equipment and the fact that we are now interested in even thinner wafers for some uses, say 200 μm, we have developed a hybrid production plan. DALSA will provide 675 μm thick CCDs where the front side is complete except for metalization. This includes all the conventional CMOS process steps. LBNL will have the wafers thinned and return them to DALSA for the ISPD in one of their furnaces. LBNL will then do the contact etch, metalization, and ITO AR coating. Locally we have developed the plasma etching technique to allow access to contacts and have acquired a 150 mm aligner so that we can do the etch and metallization steps.

2.6.8 CCD production development plan

The development plan focuses on two areas.

1. We will explore minor changes to the process flow and the layout of some CCD structures to enhance robustness at higher substrate voltages. Process flow modifications are the use of a thinner field oxide and a lower channel stop implant dose. Both reduce the electric fields in the channel stop to channel and channel stop to bulk regions. A layout modification of the p+ guard ring will reduce the possibility of a highly ionizing particle from shorting the substrate voltage power supply across the oxides.

2. We will pursue several paths of CCD production to arrive at one for SNAP production. All paths require the thinning of wafers to 200 μm. We have identified three vendors and have started qualifying them. For CCD production we have four scenarios:

1. DALSA does front-side processing up to thinning step; LBNL does thinning; DALSA does ISPD; LBNL does frontside contact-etch, metallization, and backside ITO.
2. DALSA does all steps. This required successful handling of 200 μm thick wafers in the later production steps.
3. Same as 1 except wafer is cut down from 150 mm to 100 mm; this process is known to make working CCDs.
4. LBNL does entire fabrication on 100 mm wafers.

The series of activities over the next 24 months to accomplish the above are now described.

2.6.8.1 Reorder 150 mm photodiode

We have ordered 24 additional 150 mm photodiode wafers from DALSA using an existing mask set. These will be used to develop the MSL 150 mm capabilities.

2.6.8.2 Start MSL 150 mm backside finishing processing

We will take two of six existing 150 mm CCD wafers, thin them, and send to DALSA for ISPD. The recently installed 150 mm aligner at MSL will be used to finish wafers (contact etch, metallization, ITO AR coating).

2.6.8.3 Reorder 150 mm CCD

We are finishing the quotation process for DALSA to produce 24 wafers using the existing 150 mm CCD mask set. The wafers will be 50%-50% split across nominal thickness and thin field oxide (we have used the thin field oxide in earlier photodiode runs). Six wafers will be processed with lower channel stop implant ($1.5 \times 10^{11}/\mathrm{cm}^3$). Both of the splits are targeted at enhancing the robustness of the CCDs at higher depletion voltages. Two wafers will be finished by DALSA as controls for their normal process validation.

We will divert six other wafers to the refractory metal option (Ti/TiN). They would all be finished through mask 8 of 10 masks. Two wafers would be shipped to us for front-side illumination measurement and characterization of clock line impedances. Six wafers would be kept at DALSA in case we wish to continue with front-side passivation layers, thinning, ISPD, and pad etch. If this proves successful, this would allow DALSA to do all frontside processing except pad exposure etching before thinning. The concern is that the much higher resistivity of Ti compared to Al will impact the readout clocking rate.

2.6.8.4 New 100 mm CCD

We will produce wafers at MSL with a new mask set. The CCDs are targeted at ground-based telescopes requiring reduced CCD contribution to the PSF and smaller pixels. CCDs with a repositioned p+ guard ring for higher voltage operation will be explored here. The small pixel size, higher voltage operation, and thinning techniques are all of relevance to SNAP.

2.6.8.5 New 150 mm CCD

We will produce 24 wafers at DALSA with a new set of CCD layouts. Some items to be included in the different CCDs:

- 0.5 μm clock-clock poly overlap to reduce clocking capacitance.
- Multi-tap serial register to reduce readout time.
- Repositioned guard ring to enhance higher voltage operation reliability.

The layout will be compatible with 150 mm to 100 mm cut down, preserving the integrity of some of the CCDs, in case we need to finish processing wafer using MSL's 100 mm thin wafer finishing.

2.6.8.6 SNAP 150 mm CCD (third DALSA 150 mm run)

We will produce 24 wafers at DALSA containing our best effort at the final SNAP CCD configuration. This requires layout of a new mask set. The wafer would be dominated by SNAP CCDs; existing CCD layouts can populate unused regions. The probable configuration of the SNAP CCD would contain:

- 10.5 μm pixel size
- 3.5k x 3.5k pixel count
- 4-tap readout on two edges; 8 total
- Higher voltage operation mitigations
- Reduced clock overlap capacitance

The layout will be compatible with 150 mm to 100 mm cut down for final finishing with MSL's established thin CCD process, if required.

2.6.8.7 SNAP 150 mm CCD (fourth DALSA 150 mm run)

There will be a second round of SNAP CCD pre-production. A new layout and mask set may be required, depending on the results of the previous version production.

2.6.9 CD1 planning

A major deliverable at the end of R&D is a cost and schedule for producing fully tested CCDs. From the prototyping runs we will know the foundry production costs and turn-around times and our assembly and test program will measure the yield of usable devices. From these we can establish a fabrication cost and schedule.

The yield of devices will also determine how large a production test facility we will have to construct. Our experience with the R&D test facility will establish the equipment and labor costs required for a production facility.

2.6.10 R&D deliverables

Table 7 highlights deliverables generated during the R&D effort.

Table 7. CCD test, development, and packaging deliverables

Deliverable	**Completion**
Testing	
Diffusion/Intrapixel response/crosstalk	Feb 2003
Packaging	
SNAP packaging	Apr 2003
SNAP packaging revision	Apr 2004
Development CCDs	
Photodiodes reorder complete	Jun 2002
CCD reorder	Jul 2002
New CCD layout submission	Sep 2002
SNAP CCD submission	Feb 2003
SNAP CCD submission	Dec 2003
Review of SNAP CCD format	Oct 2003
Requirements for production test facility and test procedures	Apr 2004
Fabrication & test cost and schedule	Jul 2004

2.6.11 Risk assessment

Preliminary indications are that both LBNL CCDs and commercially produced versions function well: read noise is low, CTEs are good, dark current is low, and radiation tolerance is acceptable. The main risk is selecting a CCD fabrication plan that can deliver SNAP CCDs on time. We have outlined several alternatives, one or more of which will result in SNAP CCDs.

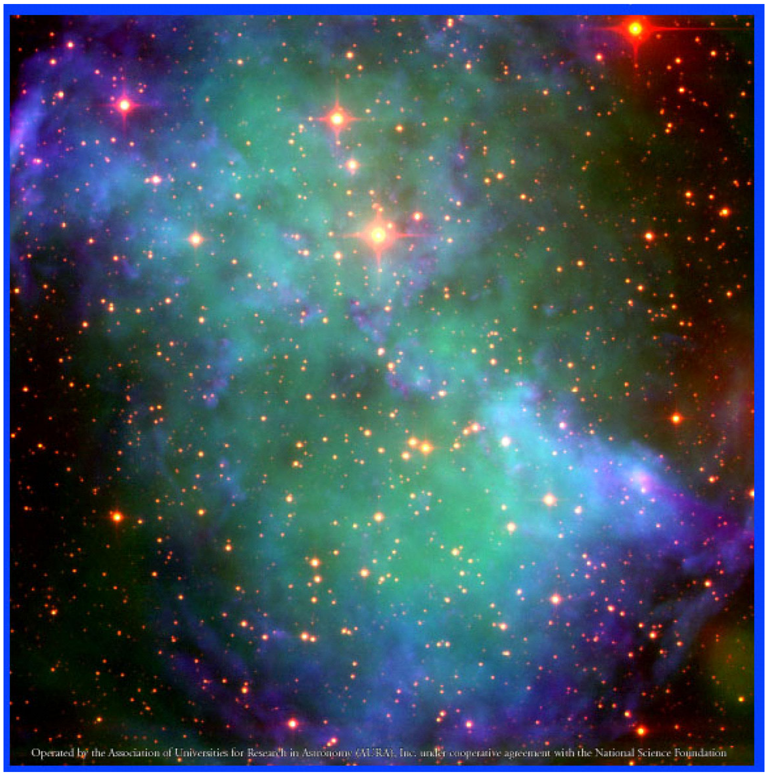


Figure 16. A false color image of the Dumbell Nebula featured on the cover of the NOAO September 2001 newsletter. The background stars are only visible because of the 1 µm wavelength response of our CCDs.

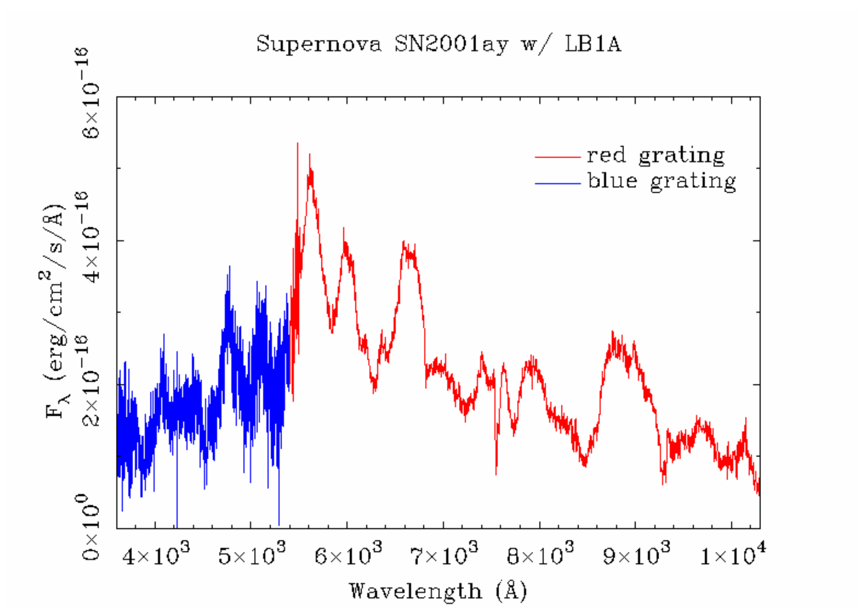


Figure 17. A supernova spectrum acquired by the LBNL Supernova Cosmology Project on the NOAO RC Spectrograph showing the extended response of our CCDs to beyond 1 µm.

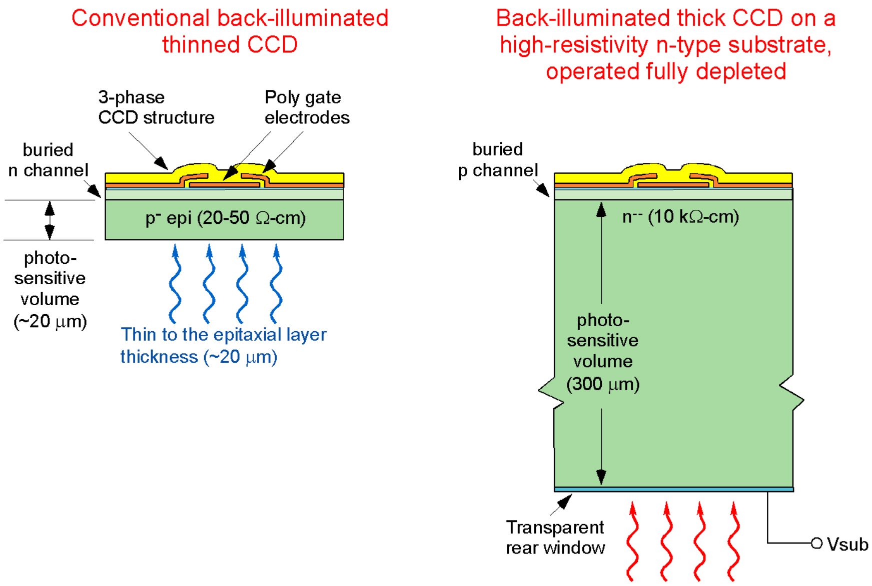


Figure 18. Architecture comparison of a conventional back-illuminated n-channel CCD and an LBNL p-channel CCD.

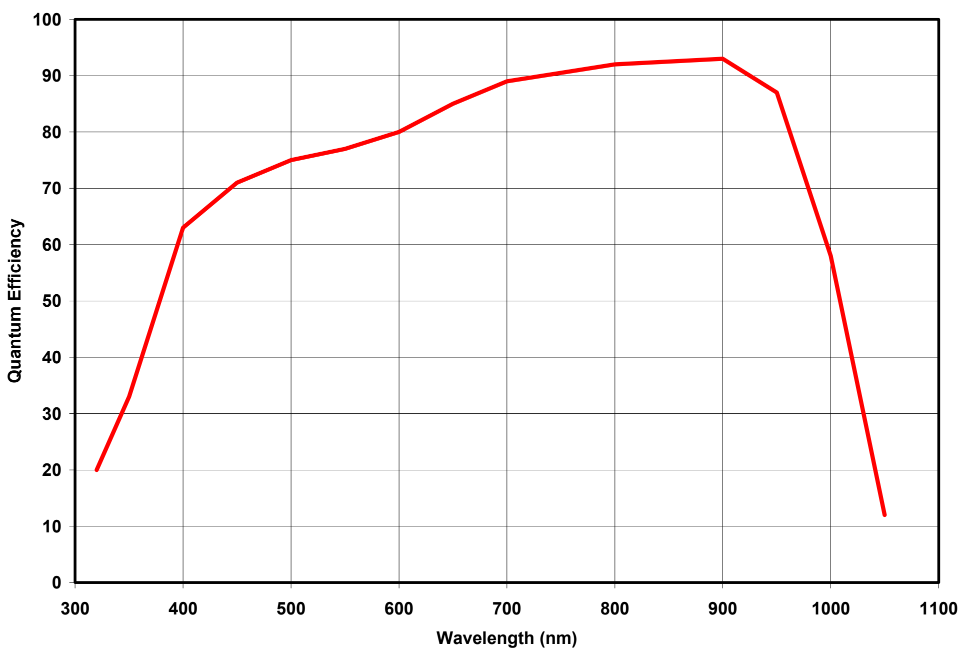


Figure 19. Quantum efficiency of LBNL CCD.

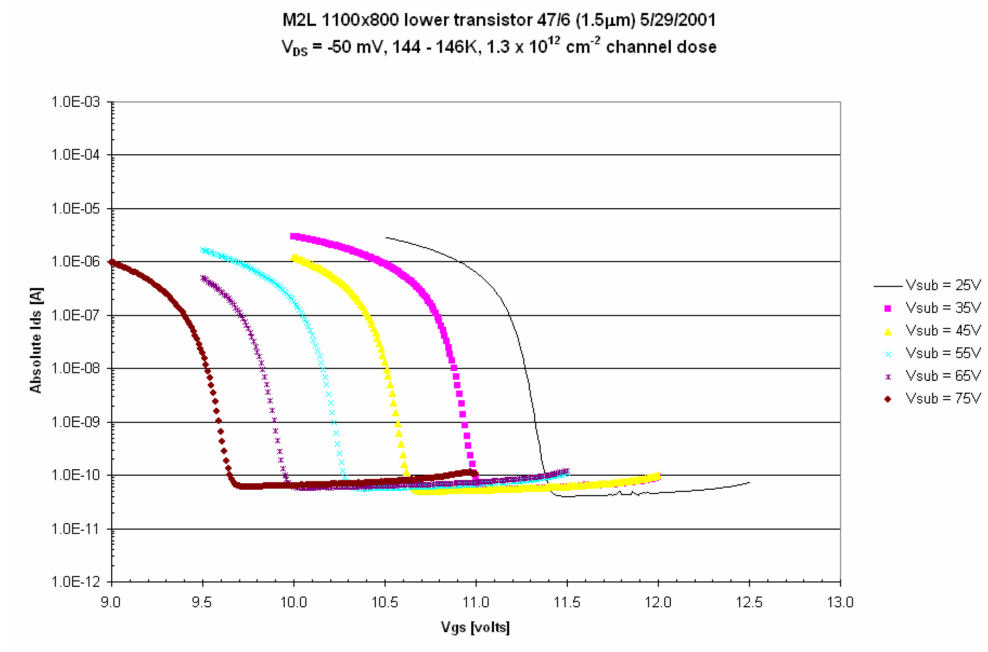


Figure 20. The subthreshold for a CCD source follower MOSFET for various substrate voltages at V_{ds} = 1 V. Measurements have been made at temperatures between 100 and 300 K. The 145 K result is shown.

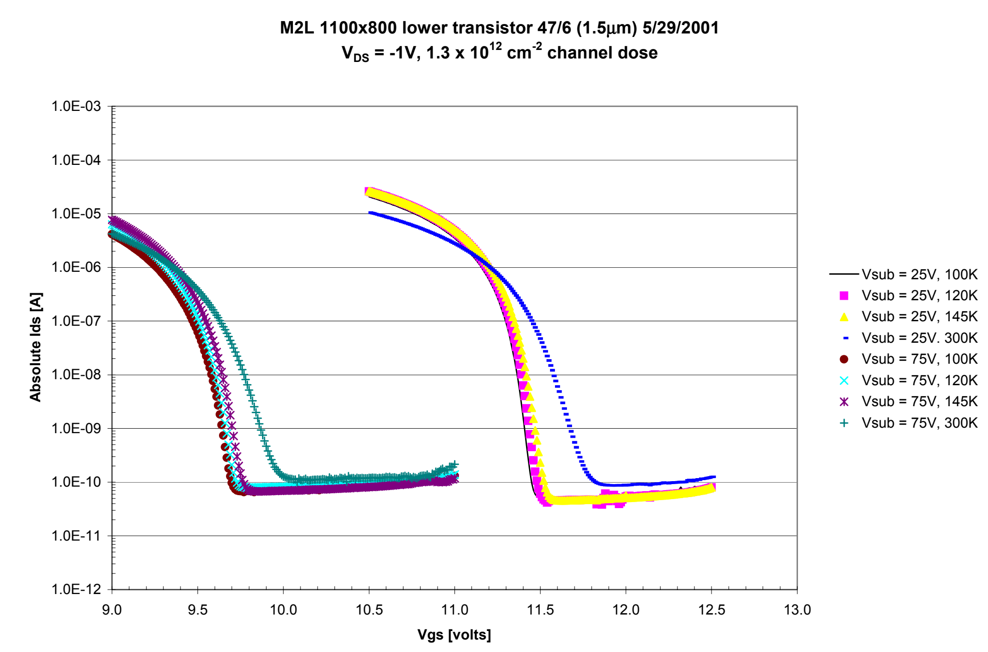


Figure 21. The subthreshold for a CCD source follower MOSFET at various substrate voltages and temperatures with V_{ds} = 1 V.

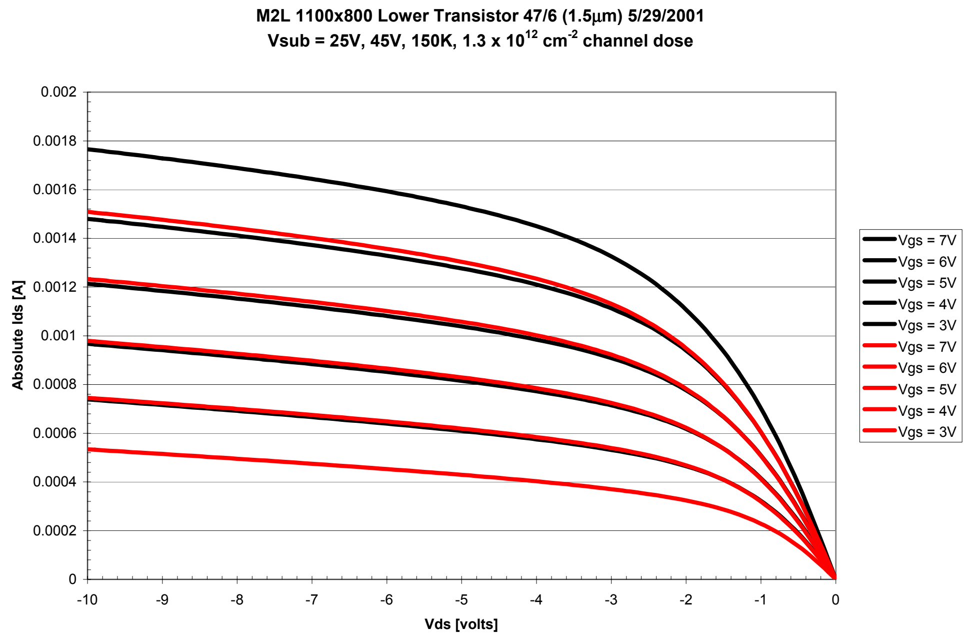


Figure 22. I-V curves for CCD output source follower MOSFET at 150 K for two substrate voltages, 25 V and 45 V.

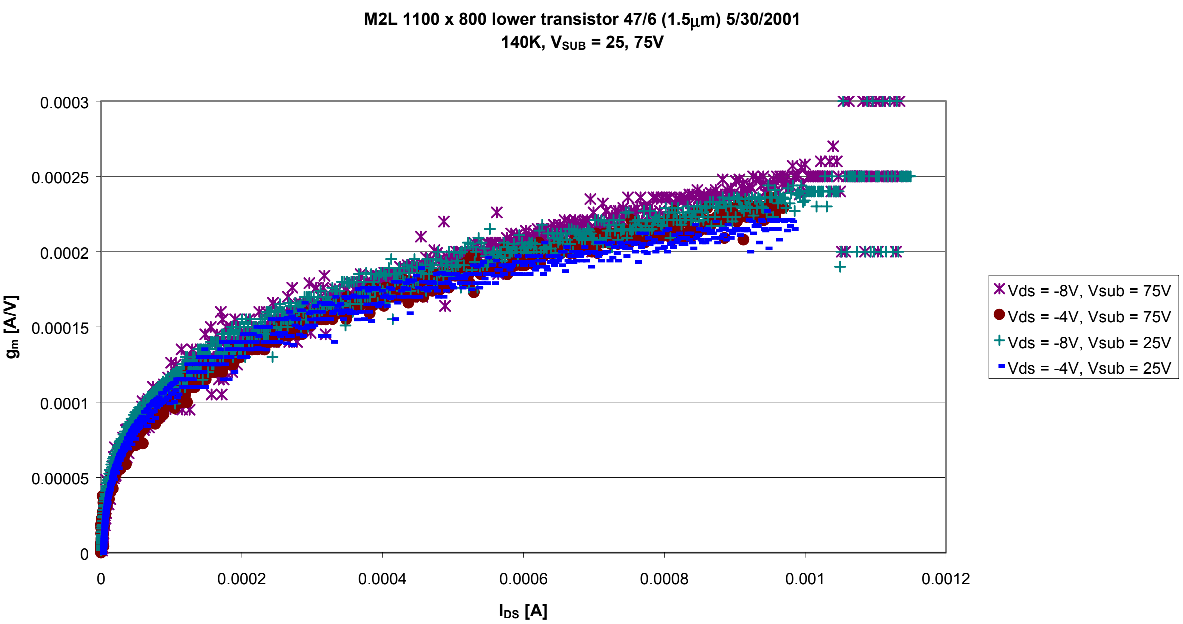


Figure 23. The g_m for a CCD source follower MOSFET at various substrate and V_{ds} voltages of 50 mV and 1 V. Measurements have been made at temperatures between 100 and 300 K. The 145 K result is shown.

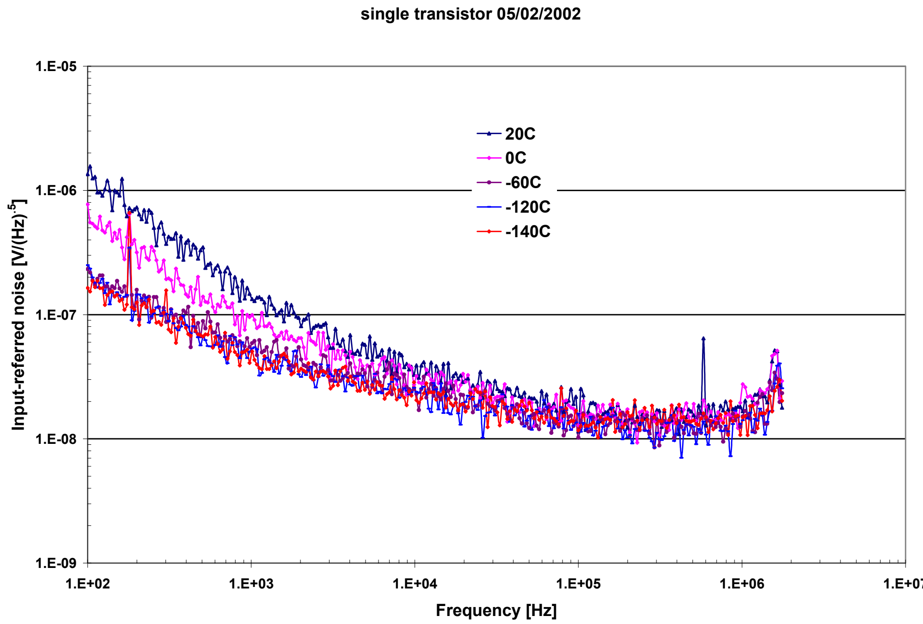


Figure 24. Noise spectral density fpr a 47/6 MOSFET source follower output stage.

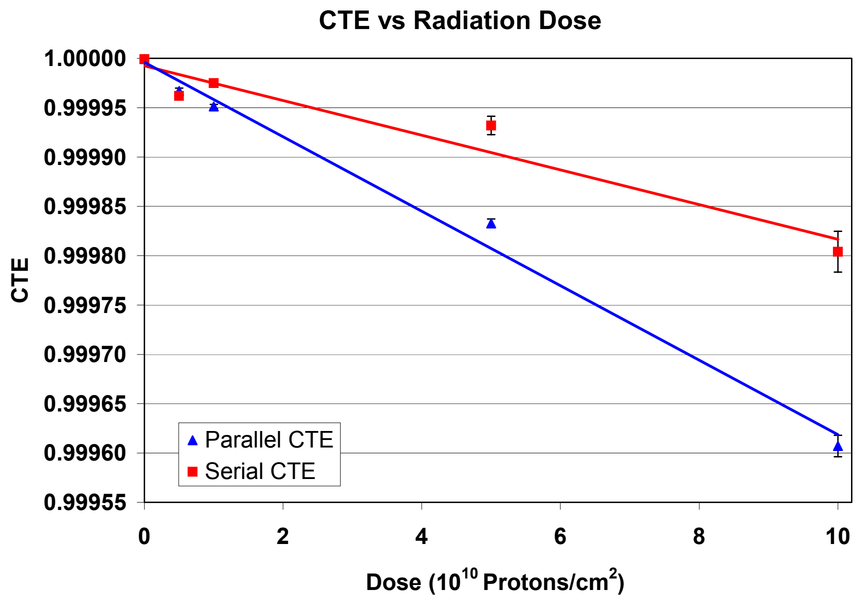


Figure 25. Serial and parallel charge transfer efficiency at 128 K as a function of 12 MeV proton dose.

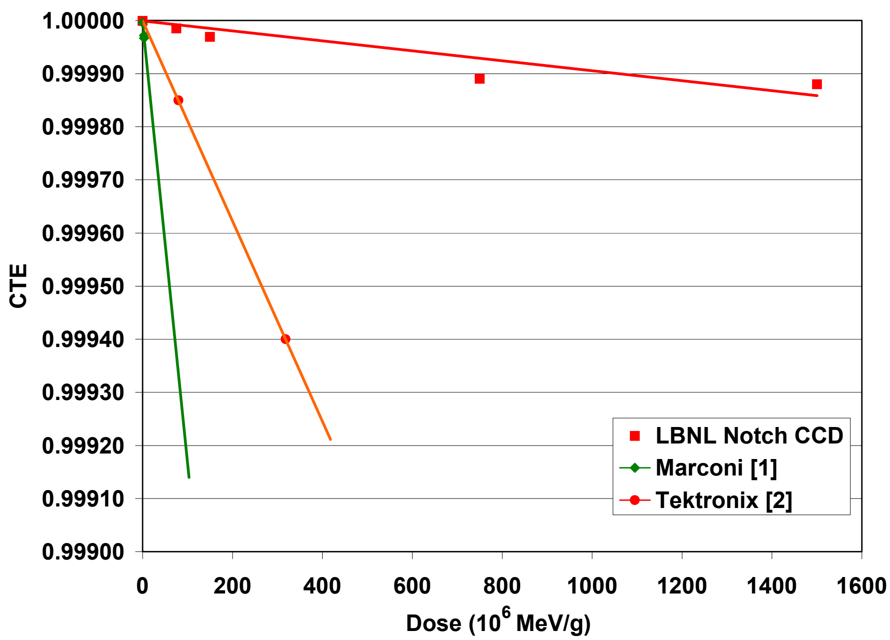


Figure 26. Comparison of LBNL CCD CTE degradation to two conventional n-channel CCDs. Since the doses were done at different proton energies, we convert them to a non-ionizing dose in MeV/g.

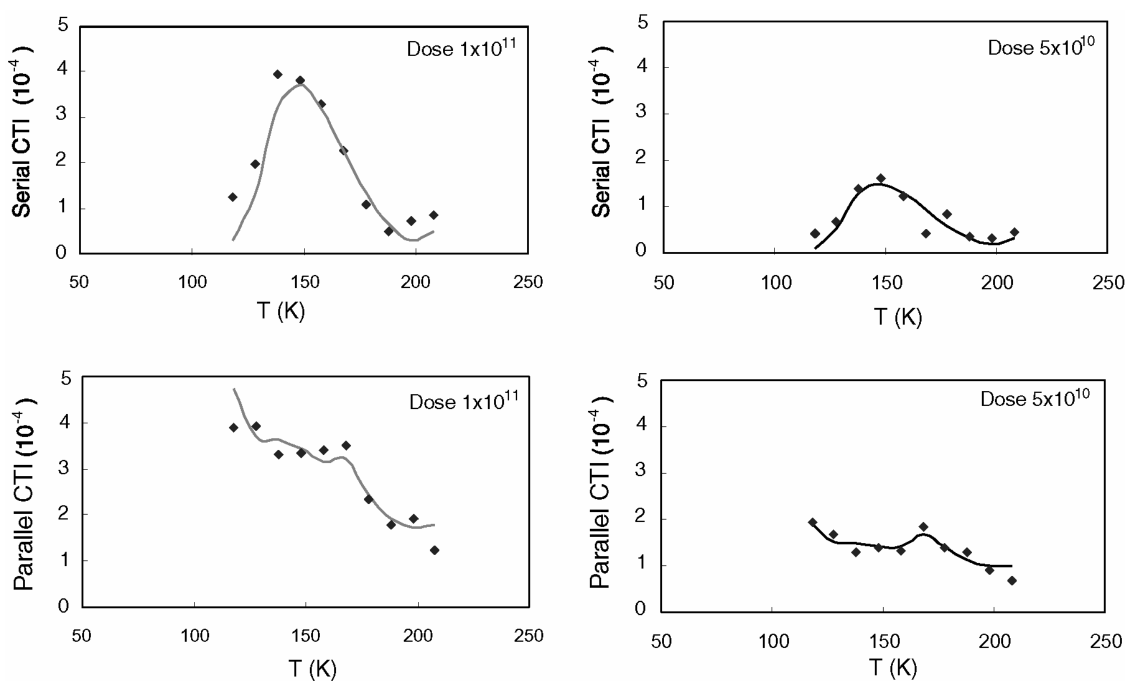


Figure 27. Representative fits of the measured CTI of two CCDs which received doses of 1×10^{11} protons/cm^2 and 5×10^{10} protons/cm^2 respectively.

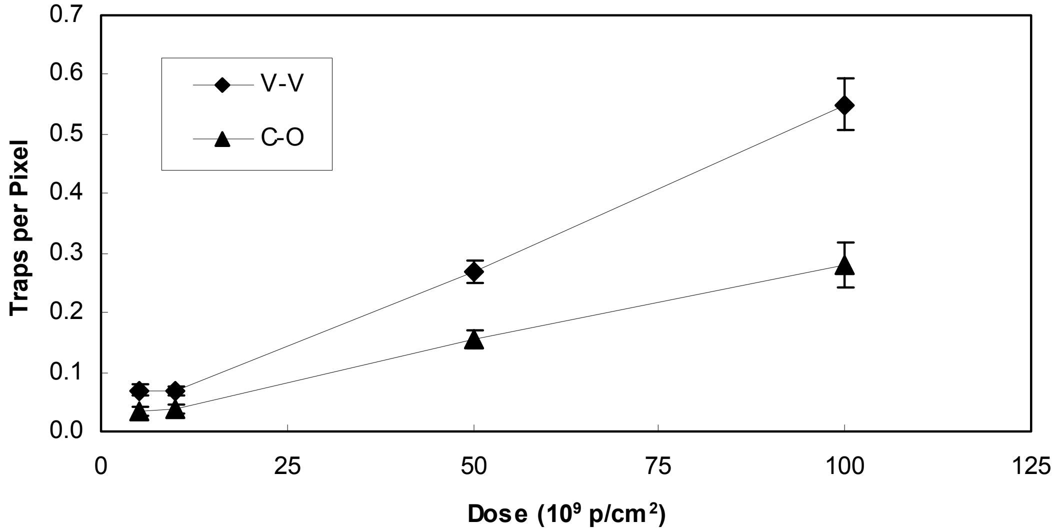


Figure 28. Dose dependence of the fitted trap densities VV (top), CO (below).

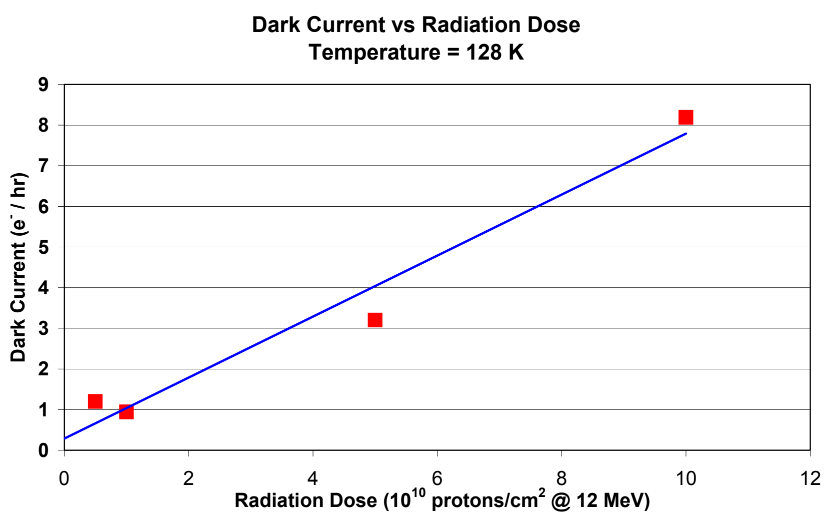


Figure 29. Dark current in electrons per 15 µm pixel per hour as a function of radiation dose.

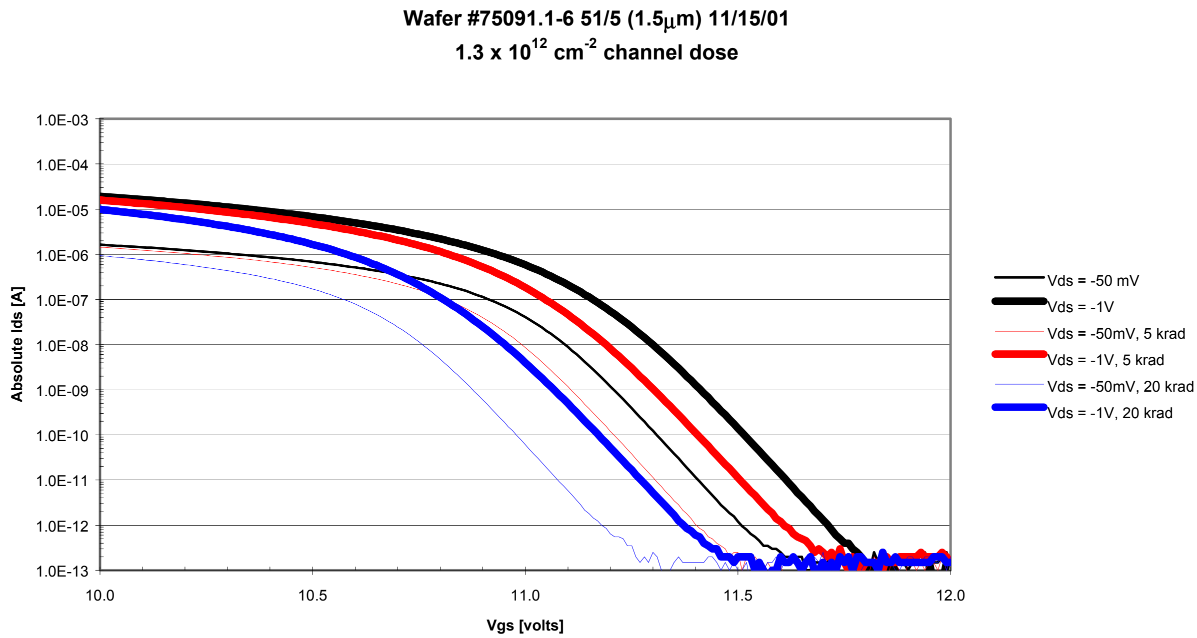


Figure 30. Subthreshold voltage shift of a 51/5 MOSFET for 0, 5, and 20 krad ^{60}Co exposures.

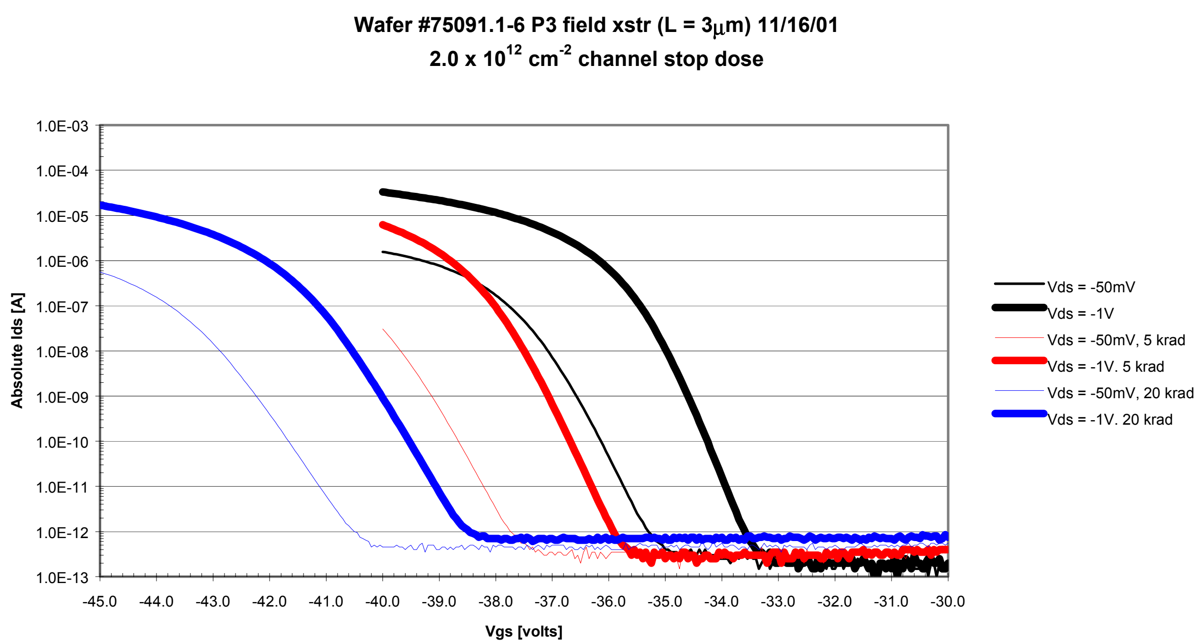


Figure 31. Subthreshold voltage shift field oxide transistor for 0, 5, and 20 krad ^{60}Co exposures.

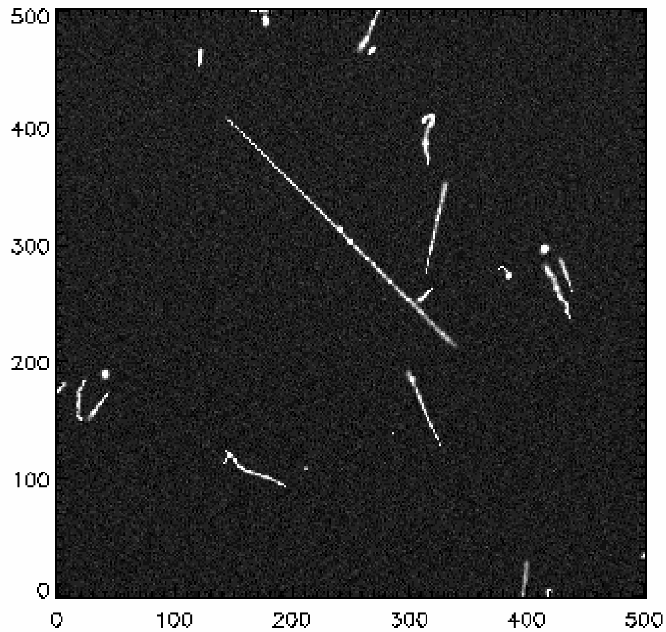


Figure 32. A 1000 second dark exposure showing the accumulation of cosmic ray tracks (straight lines) and Compton beta tracks (worm-like structures).

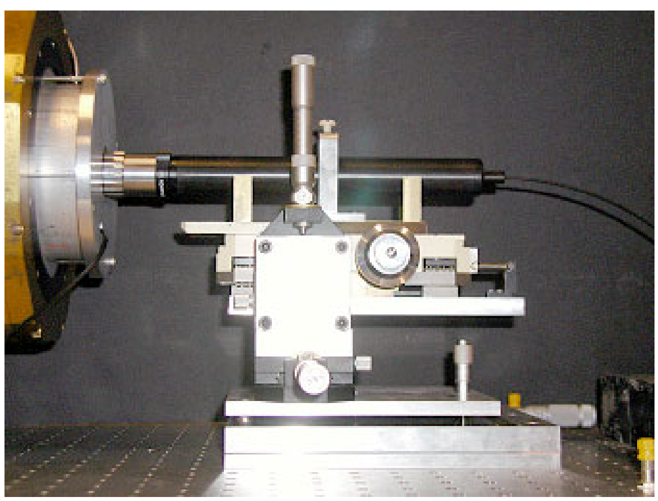


Figure 33. An x-y steppable pinhole projector for measuring cross talk, diffusion, and Intrapixel response.

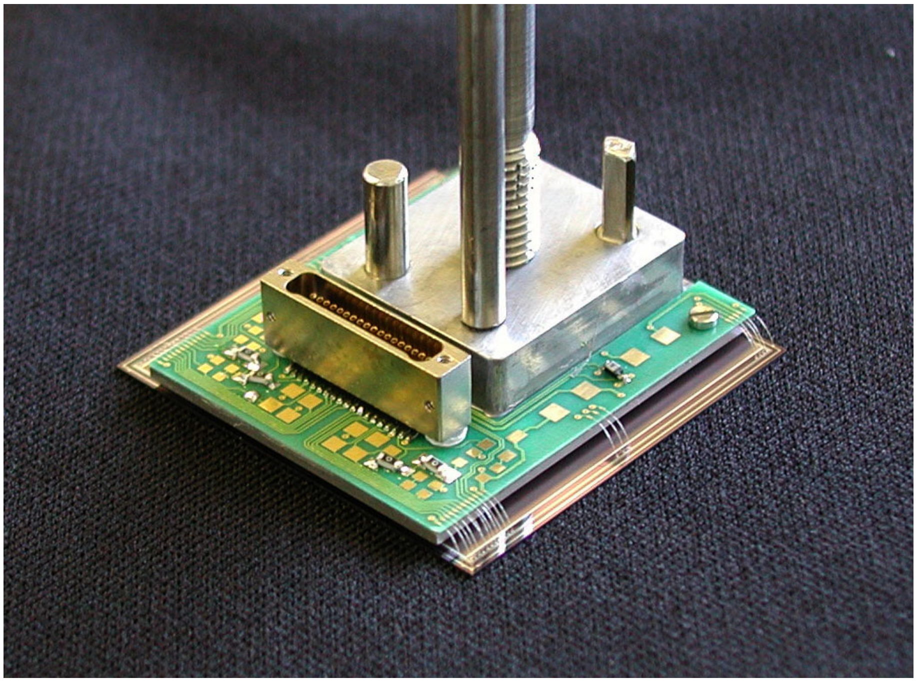


Figure 34. Four-side abuttable packaging developed for front side illuminated CCDs. The CCD is at the bottom of the stack and is glued to a molybdenum mount. A printed circuit board and wire-bonds down to the CCD can be seen providing connectivity to the connector on the left.

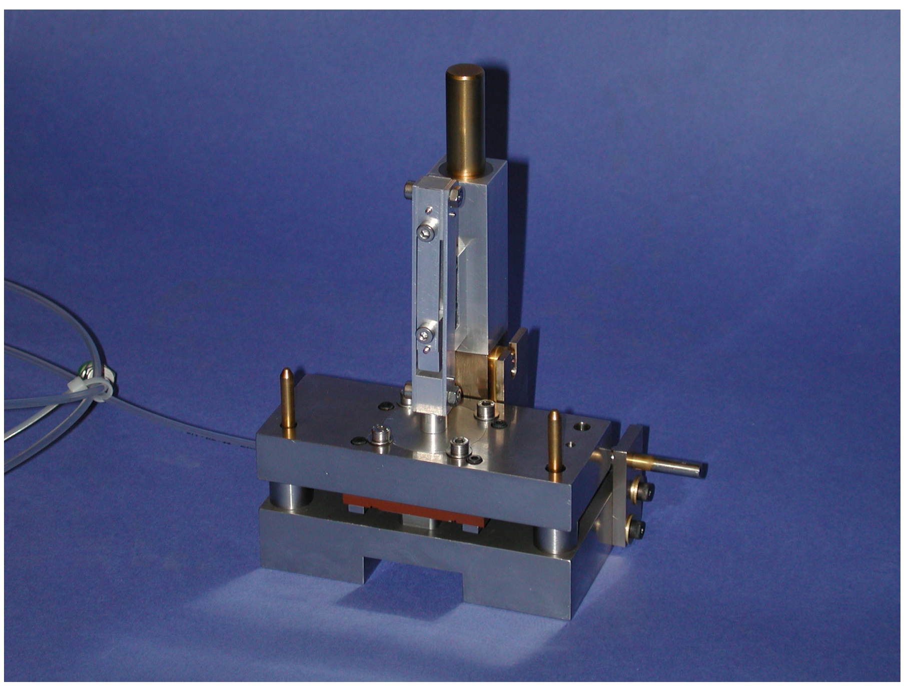


Figure 35. Precision gluing fixture used in the assembly shown in Figure 34.

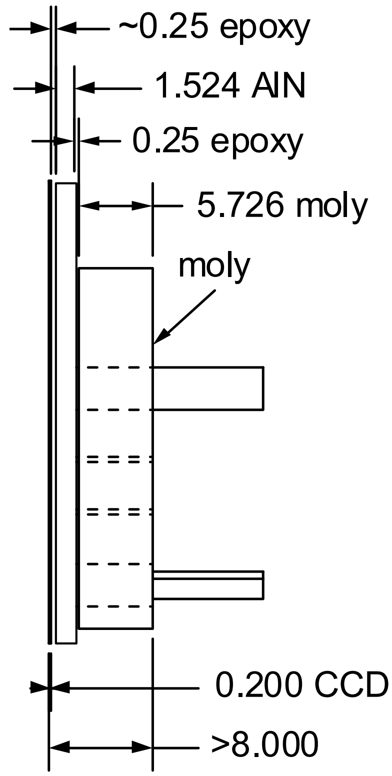


Figure 36. Sample stack of materials for a CCD mount. In this case, a CCD is glued to a 1.5 mm AlN substrate.

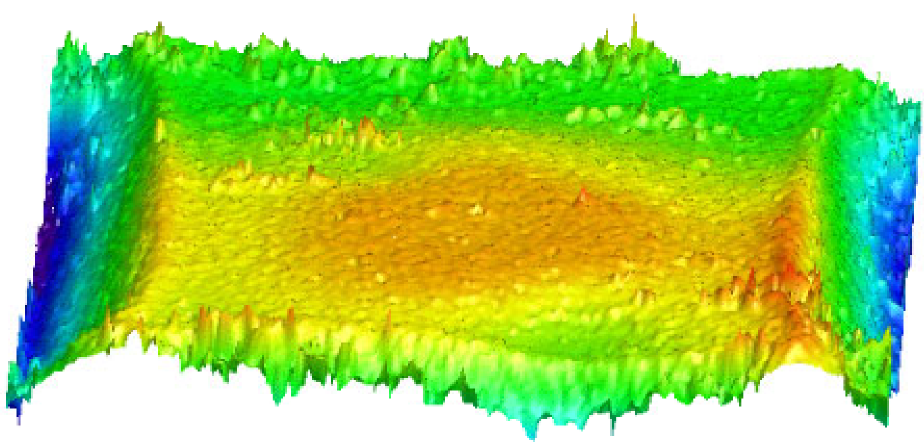


Figure 37. A speckle interferograph at 140 K of the optical surface of the package shown in Figure 36. The maximum peak to valley excursion is 6 μm.

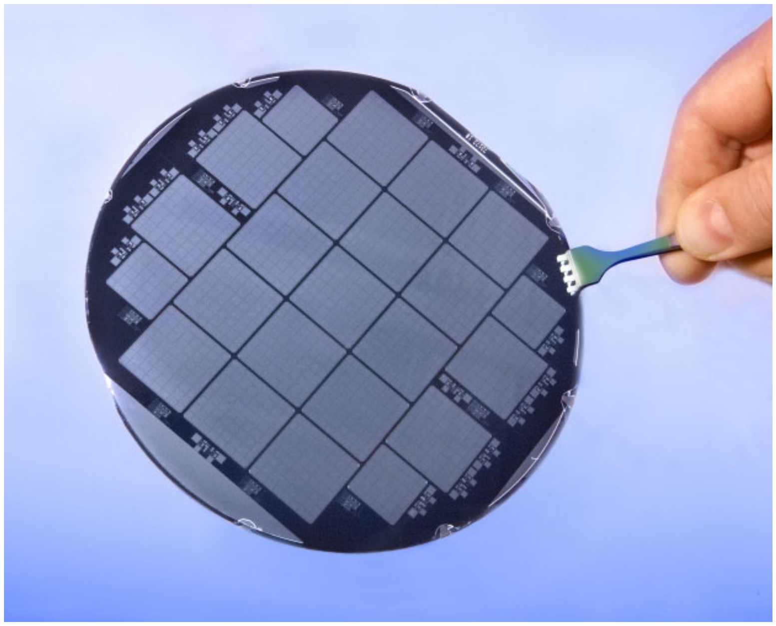


Figure 38. A 150 mm commercially fabricated photodiode wafer containing 1360 approximately 3 x 3 mm^2 photodiodes.

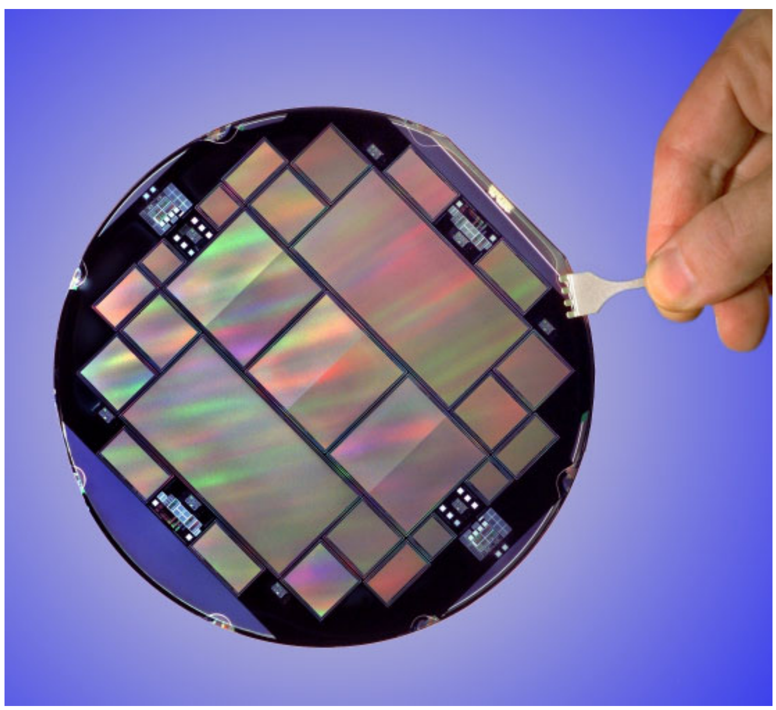


Figure 39. A 150 mm commercially fabricated wafer containing a variety of CCDs. For example, the large rectangles are 2k x 4k, 15 μm CCDs and the large squares are 2880 x 2800, 10.5 μm CCDs.

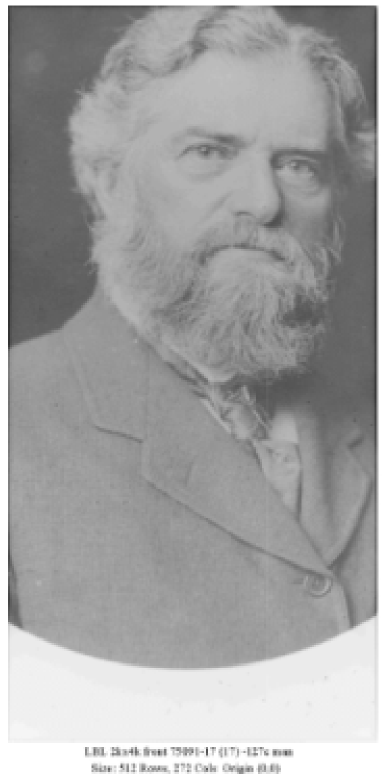


Figure 40. A front side illuminated image taken with one of the 2k x 4k, 15 µm CCDs commercially fabricated.

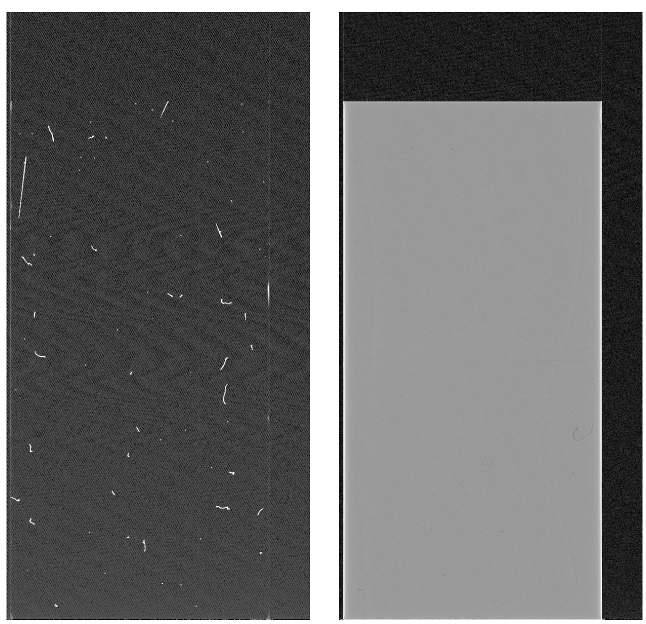


Figure 41. Fully commercially fabricated CCD. The image on the left is a 1000 s dark exposure and the image on the left is a 600 nm flat field.

2.7 On-Sensor Filter R&D

We are exploring the direct, on-sensor deposition of interference filters for SNAP. Potentially this could eliminate three issues: the mechanical support of discrete filter plates above the sensors, the (correctable) optical distortion due to the thickness of plate filters and their displacement from the sensors, and the internal reflection and scattering of bright sources that might mimic a weak source. The primary goals of this R&D program include:

1. Develop specifications for the SNAP interference filters and demonstrate that these specifications are being met. These include:
   - Transmittance at pass-band center.
   - Maximum allowable change in transmittance versus angle and temperature.
   - Pass-band edge ‘slope’
   - Out-of band transmittance.
   - Optical flatness.
   - Stability to environmental effects.
   - Sample-to-sample uniformity.

2. Demonstrate that the filter deposition process has an acceptable impact on device yields, and on the operating characteristics of the devices. Requirements include:
   - The filter deposition step should exhibit > 90% device yield.
   - Devices passing the filter deposition step should have a negligible increase in readout noise, dark current, cosmetic problems, *etc*., as a result of filter deposition.

The R&D program will proceed through the following set of steps.

2.7.1 Demonstrate basic proof of principle

Demonstrate basic proof of principle and capabilities of the vendor by depositing an interference filter on a polished silicon substrate, and measuring the transmittance of this filter and the mechanical stresses induced in the wafer as a result of the deposition process. This requires one fabrication run at Barr Associates where a representative filter will be deposited on three of four silicon wafers, with the fourth kept for control. This filter deposition step is already complete; one of the wafers is shown in Figure 42.

2.7.2 Develop provisional filter specifications

Develop provisional filter specifications and perform computer modeling to develop a filter design to meet these specs. The computer modeling will be performed by a vendor, Barr Associates.

2.7.3 Filter fabrication run #2

Deposit filters having minimum and maximum central bandpass wavelength on a number of commercial CCDs. These CCDs will be tested for noise, dark current, *etc*. before and after deposition. A sufficient number of devices will be coated to determine device yield and the uniformity of coating. In addition, a set of these devices will be subjected to a spacecraft environment to determine stability under environmental variation and over the long term. All aspects of the filter performance will be tested against the specifications provided to the vendor. Prior to this run, trade studies will be conducted to evaluate the chemical compatibility of device and filter materials, and adjust the filter composition accordingly.

Two fabrication runs at Barr Associates using 20 commercial CCDs will be performed. For testing, a camera and controller hardware will be acquired.

2.7.4 Filter fabrication run #3

Deposit a representative filter on two LBNL CCDs, holding one CCD as control. Prior to this run, trade studies conducted in the previous stage will be extended if necessary to ensure compatibility of the deposition process and filter materials with the specifics of the LBNL CCD. Readout noise, dark current, cosmetics, *etc.* of the devices under test will be measured. Environmental tests will be repeated on one of these devices.

Two fabrication runs at Barr Associates each using three to five LBNL CCDs will be performed.

2.7.5 Filter fabrication run #4

Deposit a representative filter on one HgCdTe device. This should take place upon availability of a suitable device, perhaps in conjunction with the previous fabrication run.

Two HgCdTe devices will be acquired, one as a control. An appropriate readout controller will need to be purchased.

2.7.6 Conventional filter mounting

To maintain a conventional backup option, a small amount of engineering effort will be expended to understand the impact of mounting discrete filters off the focal plane. Issues here are the positioning of the sensors to provide a support structure, the differential CTE between the support and the filter materials, and the required filter thickness and tolerances to support launch loads.

2.7.7 R&D deliverables

Table 8 lists deliverables generated during the R&D effort. The fourth fabrication run entails testing HgCdTe devices. Issues concerning vendor participation and parts costs make it difficult to establish a firm date for this final run, although it would certainly not occur before successful completion of the research on CCD devices.

Table 8. Filter deliverables.

Deliverable	Completion
Demonstrate basic proof of principle	Jun 2002.
Develop provisional filter specifications	Oct 2002
Filter Fabrication run #2	Jan 2003
Filter Fabrication run #3	May 2003
Filter Fabrication run #4	TBD
Conceptual design	Oct 2003

2.7.8 Risk assessment

The present concept of the SNAP CCD deployment is that each CCD would have four different filters in a 2×2 array. If the direct deposition of filters is successful but multiple filter deposition found to be problematic, reconsideration of the CCD size would be required to take advantage of this technology. Also, it may be challenging to validate the direct deposition of filters on HgCdTe devices, since these are expensive parts. If either issue were to prove daunting, one could fall back on a traditional, albeit non-trivial, solution consisting of mounting discrete filters over the sensors.

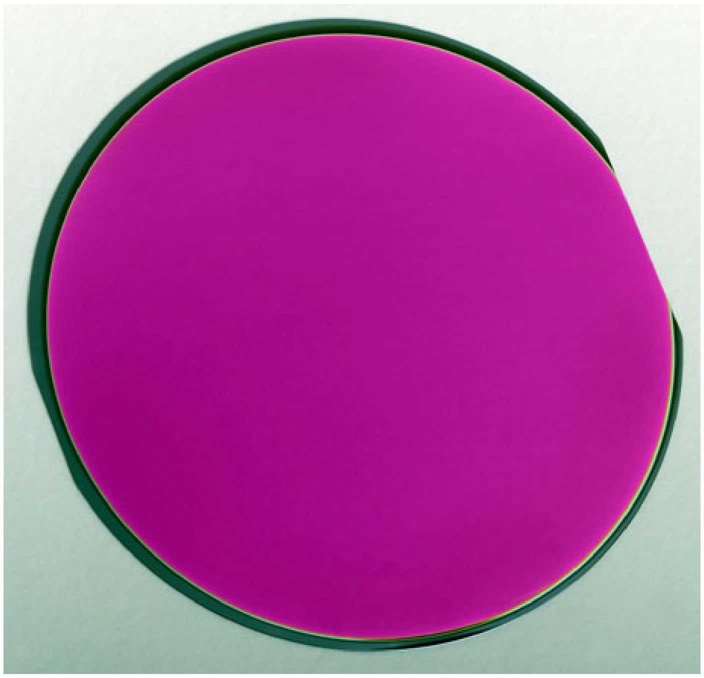


Figure 42. Reflected light from a B-band interference filter directly deposited on an indium-tin-oxide-coated 100 mm silicon wafer.

2.8 Spectrograph

The SNAP spectrograph is required to identify Type Ia supernovae and to control their luminosity determination. For each SNe candidate at peak luminosity, it must produce a confirmation spectrum. The spectrograph is the best tool to understand the composition of the SNe explosion and thereby to control and correct its magnitude. The spectrograph is also an important tool for achieving a precise spectrophotometric calibration.

2.8.1 Requirements

Working in the SNAP environment, the primary function of the spectrograph is to tag Type Ia SNe up to a redshift of 1.7. This demands high throughput and broad wavelength coverage. In addition, the spectrograph's ability to measure simultaneously the spectra of the SNe and of their host galaxies will boost significantly the observatory performance; galaxy subtraction will be straightforward and the galaxy redshift will be extracted readily in most cases.

Owing to the broad features Type Ia SNe spectra, only a moderate spectral resolution is required. The spectrograph will be optimized for a flat resolution $\lambda/\delta\lambda$ over its full wavelength range. SNe models indicate that parameters such as temperature, velocity or progenitor metallicity that are directly correlated to the magnitude can be extracted from the shape of the spectrum lines. The exposure time will be optimized for a specified accuracy on these key parameters. This leads to the requirement of a spectral resolution $\lambda/\delta\lambda \approx 100$, undersampled at one pixel per resolution element, and dithered in the spectral direction. A detector with very low noise in the visible is required for the metallicity determination, which is sensitive mostly to the UV part of the spectrum. These requirements lead to the baseline specifications shown in Table 9.

Table 9. Spectrograph main characteristics.

Item	**Visible**	**IR**
Wavelength coverage μm	0.35-0.98	0.98-1.70
Field of view	3.0" x 3.0"	3.0" x 3.0"
Spatial resolution element (arc-sec)	0.15	0.15
Number of slices	20	20
Spectral resolution, $\lambda/\delta\lambda$	100	100

2.8.2 The instrument concept

We propose an integral field spectrograph based on a reflective image slicer. During the past year, we have explored alternatives and conducted an in-depth analysis of different specific designs. To select the best possible approach, we performed a trade-off analysis that balanced the performance of these designs.

Integral field spectroscopy is now a mature technique used in many ground based instruments, with the latest generation having been developed for 8-meter telescopes like Gemini and VLT (see *e.g.,* Bacon *et al*., 1999; Le Fèvre *et al*., 2000; Davies *et al*., 1998). The principle is simple: acquire spectra of each resolution element in a contiguous sky area. In this way it is possible to reconstruct a 3D image (x,y,λ) of the sky. We can measure simultaneously the spectrum of the SNe candidate and that of the host galaxy without slit losses and without imposing stringent requirements on the pointing capabilities of the spacecraft.

The proposed technical solution for this integral field spectrograph is based on a slicer unit (*e.g.*, NGST IFMOS study, Le Fèvre *et al*., 1999, ASP conference series, Volume 207, 313). The basic principle is identified in Figure 43: the 2D field of interest is sliced into several strips, with the slices rearranged to enter the spectrograph as the equivalent of one single long slit. This concept has several major advantages compared to a long slit spectrograph. Spectra are acquired for all resolved spatial elements of a contiguous area on the sky; there are no slit losses; and the telescope pointing accuracy is relaxed to a fraction of the observed field, rather than a fraction of the slit width, expediting data acquisition.

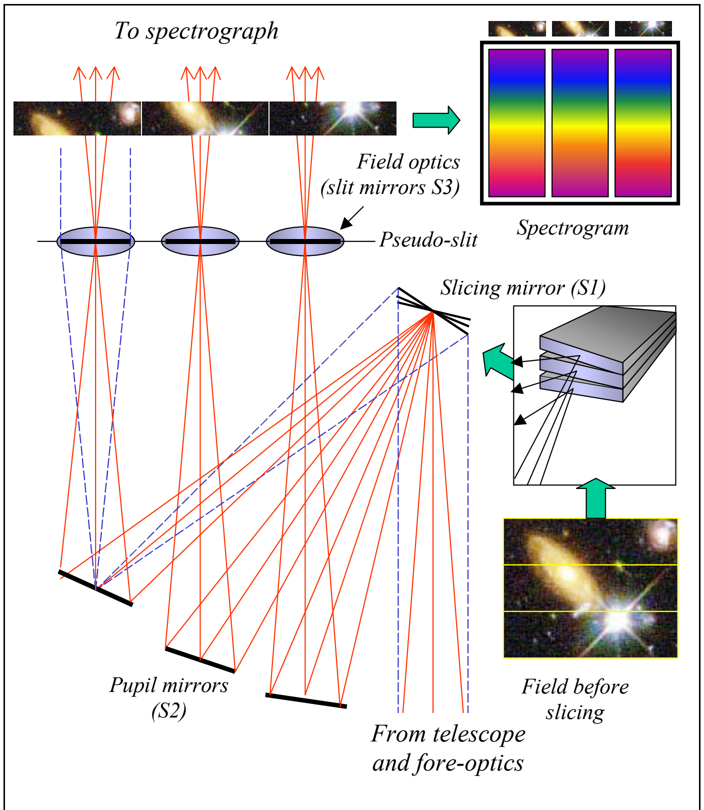


Figure 43. Image slicer principle (courtesy J. Allington-Smith, Durham U.)

2.8.3 Baseline design

The instrument functionalities are summarized in the instrument block diagram shown in Figure 44. Principal components are described below.

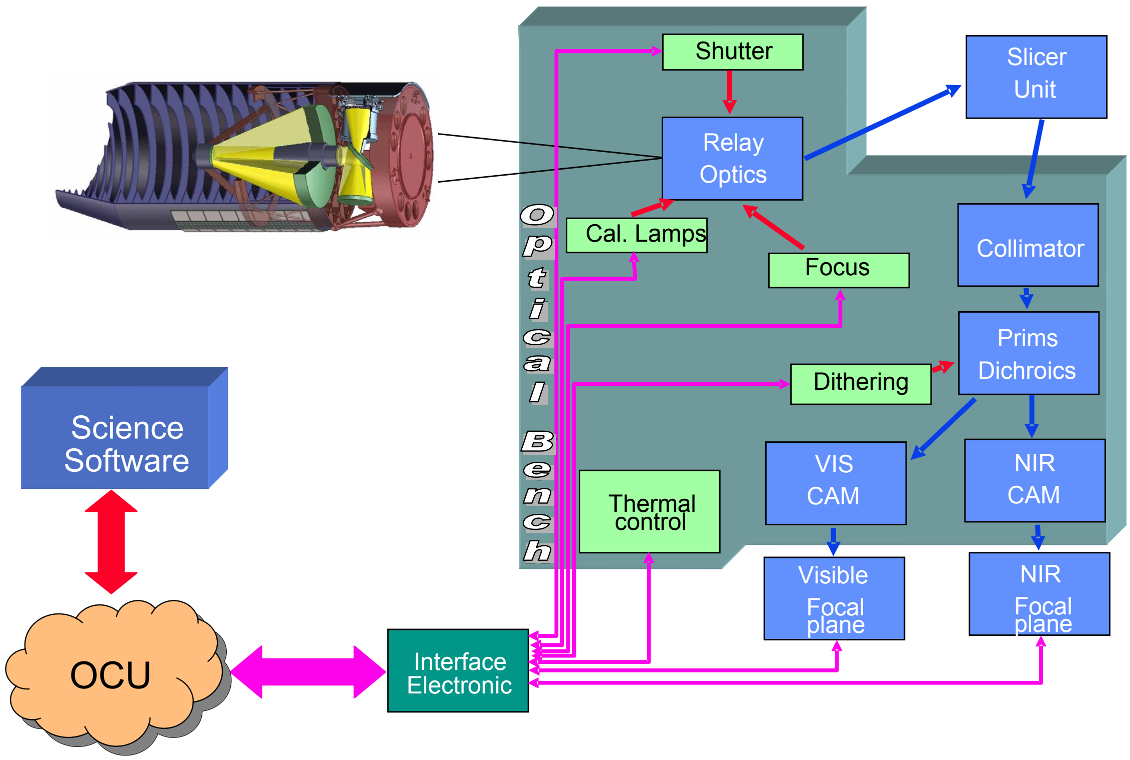


Figure 44. Instrument block diagram.

2.8.3.1 Relay optics

This unit is the interface between the telescope beam and the instrument. The optical solution is highly dependent on the implementation of the instrument. The definition of this optical system requires the knowledge of the spectrograph position with respect to the telescope focal plane. The beam can be picked off wherever it is most convenient for the overall instrument. It will be beneficial to correct some telescope aberrations within this optical system. A simple, easily conceived three-mirror configuration should be sufficient to satisfy these requirements.

2.8.3.2 Slicer unit

The slicer unit acts as a field reformatter. The principle is to slice a 2D field of view into long strips and optically align all the strips to a long spectrograph entrance slit. The slicing mirror is comprised of a stack of slicers. Each slicer has an optically active spherical surface on one edge (see Figure 45). A line of “pupil” mirrors does the reformatting. Each pupil mirror sends the beam to a slit mirror, which adapts the pupil to the entrance of the spectrograph.

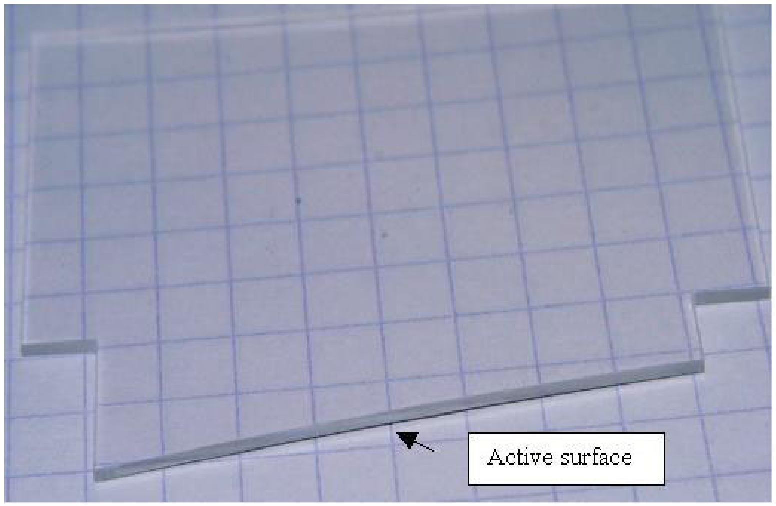


Figure 45. Picture of one silica individual slice (40 mm x 0.9 mm).

The long thin active surface of each individual slicer will produce a large diffraction effect. In order to minimize flux losses to a few percent, the spectrograph entrance pupil must be oversized. A combined theoretical and experimental approach is underway at LAM to define the optimum entrance pupil (in the infrared bands 1-5 μm).

The baseline requirements on the slicer unit are an accuracy of $\leq \lambda/10$ rms on the optical surfaces and a surface roughness of ≤ 5 nm rms (existing prototypes fully meet these specifications).

2.8.3.3 Optical bench

Thanks to the moderate beam aperture and field of view, the spectrograph optics will be straightforward. The baseline is a classical: one collimator mirror, one prism with a dichroic crystal, and two camera mirrors are required. Using spherical shapes for all the mirrors would provide an adequately sharp image, but using aspherical mirrors will make it possible to have a very compact spectrograph. The prism solution is well adapted to the requirement of a flat resolution over the whole wavelength range. The dichroic crystal allows covering two channels simultaneously: one for the visible (*e.g.*, 0.35-0.98 μm) and one for the infrared (0.98-1.70 μm).

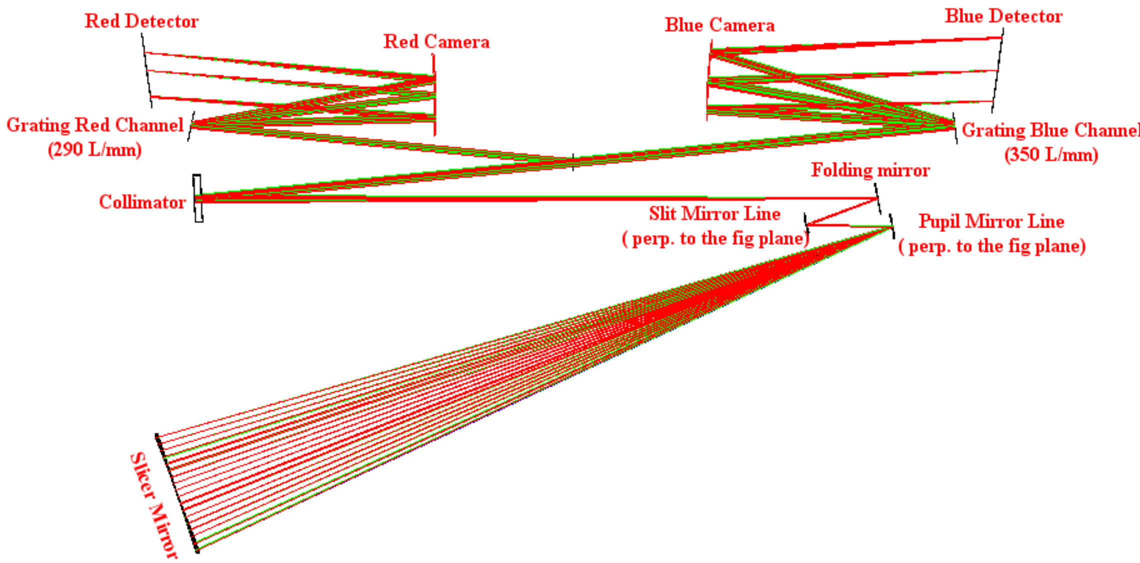


Figure 46. The global spectrograph instrument.

The oversized pupil will catch >95% of the flux at 0.6 μm, and at worst 85% of the flux at 1.7 μm. This optimization will be performed during the conceptual phase.

2.8.3.4 Detectors

In the visible, the main goals are high quantum efficiency and very low noise. Given concerns over degradation due to radiation exposure and the poor performance of thinned conventional CCDs in the red part of the visible, we will study carefully the applicability of the LBNL CCDs. Thinned, backside-illuminated, low-noise conventional CCDs of 1024×1024 pixels are an alternative option.

In the IR, some factors constrain the detector technologies. The overall temperature for the SNAP instruments will be fixed in the range 130–140 K and the spectrograph must operate in this range. While keeping noise figures low, the cutoff wavelength of the array must be as close as possible to 1.7 μm. A 1024×1024 HgCdTe array with 18 μm pixels from Rockwell is under consideration.

The choice of visible and IR detectors will be done in close collaboration with the teams designing the imager in order to maintain the simplest overall solution for SNAP.

A detailed list of the performance specifications for the detectors is listed on Table 10. To achieve the listed performance in read noise and dark current, a multiple sampling technique is required. To optimize exposure time, the impact of the rate of cosmic rays on the readout noise is under present study.

Table 10. Spectrograph detector specifications

	Visible	**IR**
Detector size	1k × 1k	1k × 1k
Pixel size	15-20 μm	18 μm
Detector temperature(K)	140	140
<QE>(%)	80	60
Read noise(e)	2	5
Dark current(e/pixel/s)	0.001	0.02

2.8.3.5 Structure

In order to fulfill the requirements for the SNAP spectrometer design, we propose to carry out a study of materials early in the design phase, with the following properties:

- low density
- high Young modulus
- small CTE
- good thermal conductivity
- good compatibility with Zérodur (used for optics)

The unquantifiable criteria in Table 11 are denoted by “A” to “D” (A = excellent).

Table 11. Spectrograph material trade-off table

	Zérodur	**Invar**	**SiC**	**Mo**	**Al (alloy)**	**Be**
Young’ modulus	70 000	210 000	311 000	330 000	70 000	300 000
Density	2.2	8.1	2.9	10.2	2.7	1.9
CTE @ 300K	0.03	1.4	2.6	5.1	24	12
CTE @ 30 K	-0.7	0.3			1.5	0.1
Thermal cond. @ 300K	1.3	13.5	156	138	150	180
Manufacturing	B	A	C	B	A	B
Machining	B	A	B	B	A	C
Cost	B	B	B	B	A	C

The selection of the best candidate will take place in Fall 2003. Associated with this trade-off, we will design the structure of the spectrograph. Figure 47 and Figure 48 show examples of slicer unit structures.

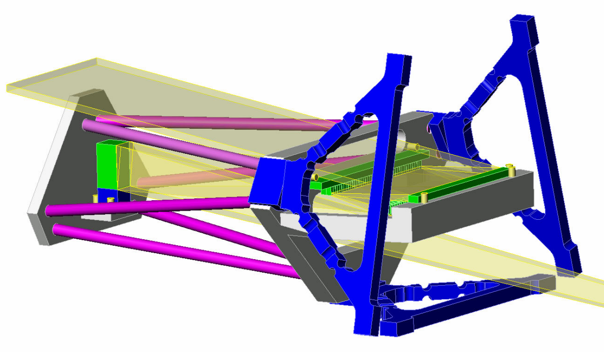


Figure 47. An example of a serrurier truss structure for a slicer unit.

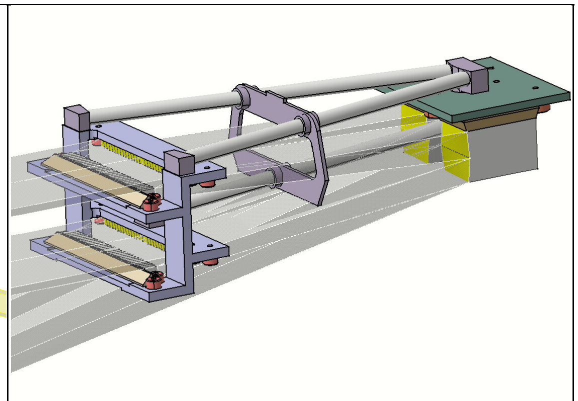


Figure 48. Another example of structure for a slicer unit.

2.8.3.6 Structural and thermo-elastic analysis

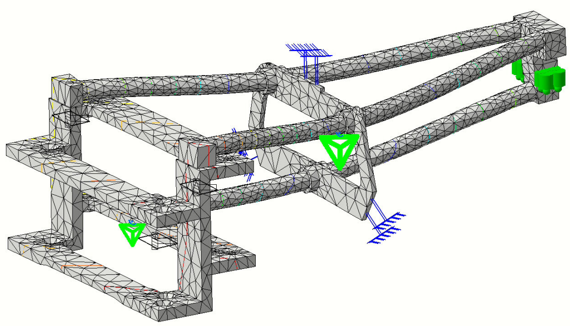


Figure 49. Slicer structure modal analysis example.

We will perform a modal and thermo-elastic analysis in order to check the stability of the spectrograph with respect to temperature variations during operation. The analysis will insure the survival of the instrument at launch. Thermal deformations during cooling and the resulting optical alignment stability requirement will be studied. The material will be validated and the dimensions will be optimized, taking into account appropriate safety factors.

2.8.3.7 Dithering

Spatial dithering occurs randomly through pointing of the instrument. To implement a controlled spectral dithering, a simple solution that consists of moving the prism between two fixed positions by means of a mechanical or thermal actuator is under evaluation. This should not be technically difficult.

2.8.4 R&D activities

Two main activities have been identified as R&D studies for the two next years: one, determine that a slicer adapted to the requirements of SNAP achieves the performance specifications; and two, development of the focal plane detectors.

2.8.4.1 <u>Slicer R&D</u>

The proposed image slicer is of the same type as the one studied in the context of the NGST near-IR spectrograph (Allington-Smith *et al*., 1999; Le Fèvre *et al*., 1999). This technology has been ranked at NASA readiness level 5 by a panel of NASA experts in the context of the concept appraisal of pre-phase A NGST studies. The readiness level 6 is required to be "space qualified." Prototyping activities are ongoing at Laboratoire d'Astrophysique de Marseille (LAM) and in collaboration with other European institutes to validate this technology both for large ground-based telescopes and for space applications, under funding by various agencies including ESA, CNRS and CNES. The R&D effort necessary to adapt this concept to the SNAP requirements therefore meshes nicely with on-going activities and will be in time with the R&D phase. Specifically, we have an ongoing program to qualify image slicers for space instrumentation. We are now in the process of developing a realistic prototype for a space-qualified unit based on Zerodur-glass slices. Several slices have been successfully manufactured to specifications (Figure 45). This prototype adequately represents the SNAP application. The road map of the R&D is presented in Figure 50.

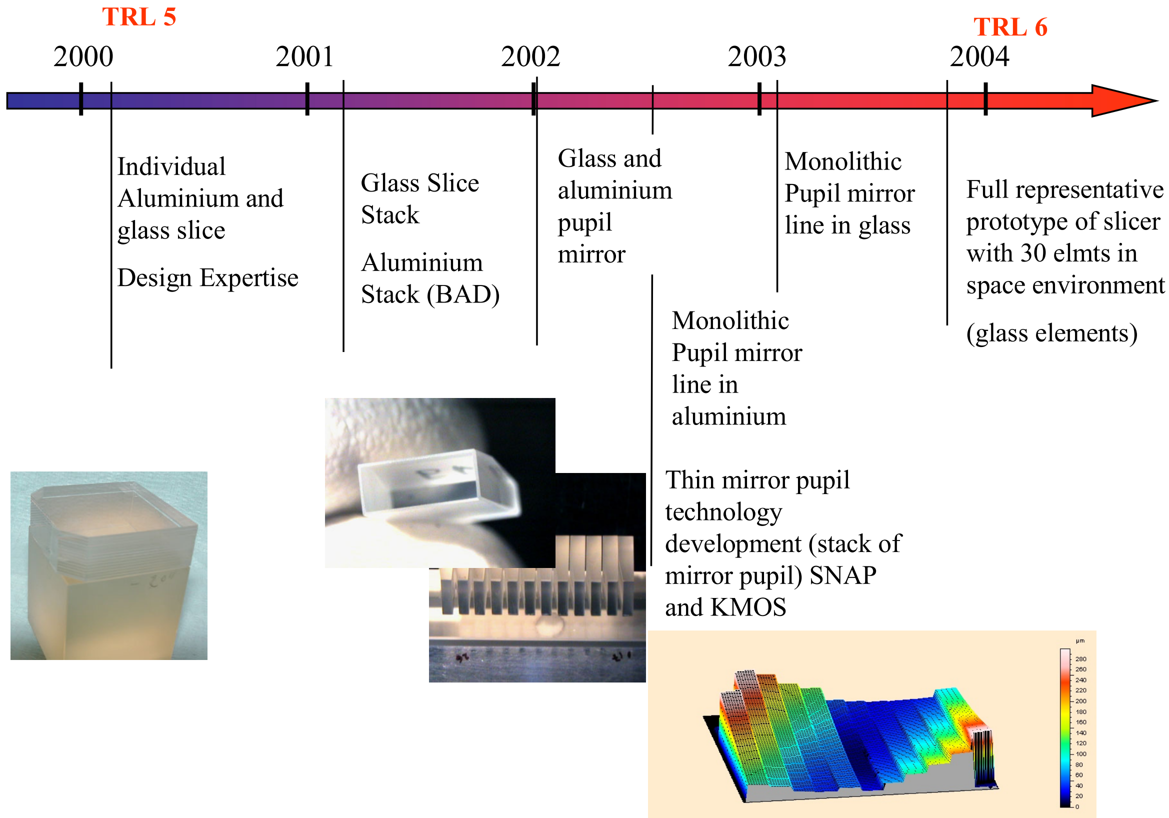


Figure 50. Slicer development road map.

2.8.4.2 Detector R&D

In the next two years a focal plane specification must be developed firstly to choose and characterize the detectors, and secondly to define the readout electronics and prepare the thermal and mechanical concept. The schedule is included in the overall one in Figure 51. The idea is first to conduct an expert study on the detector and electronics. Afterward, we propose to make a trade-off and select one solution to be studied, tested and characterized by the end of the R&D phase. The output document will be a development plan for phase B/C/D. A general R&D effort in France, which will be supported by IN2P3/CNRS and CNES, is planned to develop expertise on electronics for IR detectors (E. Barrelet *et al.*). The spectrograph study will fit into this effort.

2.8.4.3 Calibration

To perform spectrophotometry, a full strategy of calibration on ground, balloon or space instruments must be set up. A careful study of the problem and the impact on the spectrograph will be evaluated in collaboration with the SNAP calibration group for the end of 2003. The monitoring of the spectrograph PSF stability and its impact on the physics will be considered carefully as part of this study.

2.8.4.4 Software development

A full simulation including all instrumental effects, packaged in the SNAP software, will be developed to cover all instrumental studies. A fast simulation will be used independently to simulate and study the physics. Preliminary work will start on the design of the spectrograph's data processing pipeline, which will be embedded in the SNAP pipeline. The development of this software will be linked with the general effort in Europe to develop processing codes for 3D spectrograph applications (Euro-3D). Investigations on the calibration software and data monitoring will be done in parallel.

2.8.5 Risk assessment

Our preliminary analysis indicates that the image slicer and the detectors are the only components requiring effort during the R&D phase to mitigate risk later in the project. All other components are well within the current technology. Assessing the required high throughput through analysis of 1) alignment, 2) construction, and 3) design simplicity will be an additional goal fo the R&D period.

2.8.6 R&D deliverables

Table 12 lists deliverables generated during the R&D effort.

Table 12. Spectrograph deliverables schedule.

Deliverable	Completion
Science and Technical trade study	Jan 2003
Spectrograph pre-conceptual design	Mar 2003
Focal plane concept review	Jan 2004
Slicer Prototype report	Mar 2004
Conceptual design report	Jul 2004
Construction cost and schedule	Jul 2004

2.8.7 Schedule summary

The first milestone is the CD0 (mid 2003), which will start the R&D Phase. The planning for the next two years has then been phased with this milestone up to the CDR at the end of 2004.

Figure 51 shows the development schedule to proceed to the CDR.

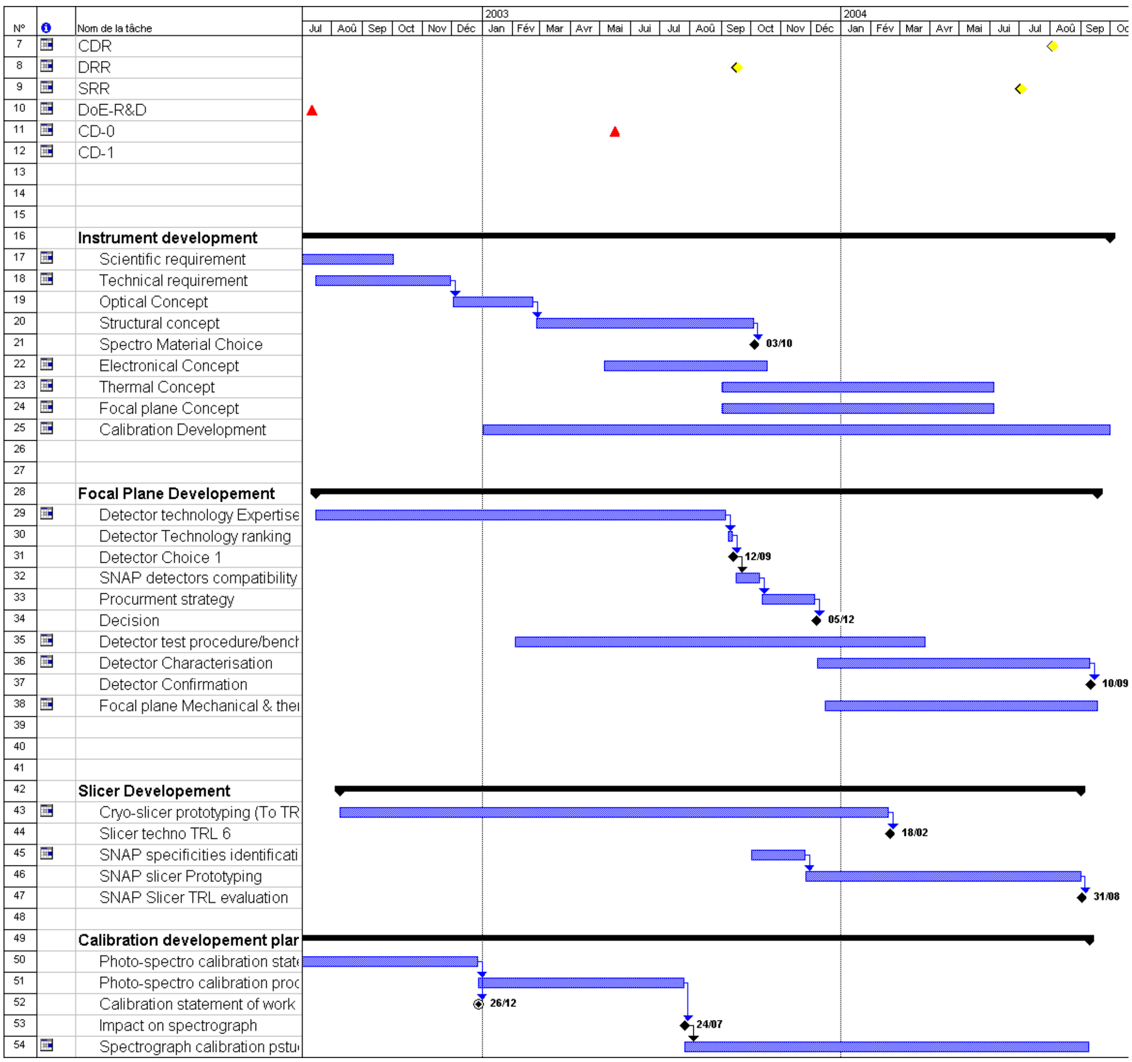


Figure 51. Spectrograph development schedule summary.

2.9 Data Acquisition and Control

SNAP generates prodigious amounts of data and determining how to handle it in the satellite is another activity during the R&D phase. Data generation time profiles, different processing options, telemetry rates, and ground station visibility hours all need to be modeled to arrive at an optimal conceptual design. An important R&D task is to document all the control and command functions required by the instruments and their interface to the on-board data management system. This research will generate critical input into the satellite design: weight, power, and volume of processors and memories; required telemetry bandwidth; and the number and availability of ground stations required.

The R&D tasks described below are

- Develop concepts.
- Perform Implementation research.
- Develop requirements.
- CDR planning.

The readout electronics transmits data for 20 seconds approximately every 300 seconds during photometric observations, outputting a total of 12 Gbits/image uncompressed. The data are stored and over three Tb are transmitted every three days using a 300 Mbs downlink for approximately three hours. Collecting, processing, and making this data available to the telemetry system are challenging. As part of the challenge, we need to consider such items as redundancy, non-propagating failure modes, power, and packaging.

The SNAP instruments will have both common and unique needs to operate them. Under the research part of this activity, we will document the configuration and operational requirements of the instruments. These will eventually map into the low level command set to be executed under the direction of the observation program script periodically uploaded from the ground.

Figure 52 shows the potential interactions of the instrument data, data acquisition, instrument controls, and the satellite. The partitioning of responsibilities is illustrative only.

All CCD and HgCdTe devices can in principle be controlled and digitized with a common, modestly flexible electronics system. We have set the goal that any new controller technology will be compatible with all the pixel technologies used in SNAP. Conventional CCD controllers are quite bulky and, more important, power hungry. Scaling up to the SNAP imager would require a power consumption of 1200 W. In a later section we describe development work on application specific integrated circuits for analog signal processing and digitization. This is motivated by reduced power and volume, higher integration and reliability, and radiation hardiness.

2.9.1 Progress in the Past Year

In the past year we have developed an essential model of the SNAP electronics that covers all use cases for the wide-field imager sensors, the spectrograph sensors and the star guiders. The essential model describes the different modes of operation, including fixed duration exposures followed by readout, dark exposures, flat field exposures, *etc*. In Figure 52 the overall block diagram for the SNAP instrument electronics is shown; this is the basis for the essential model. The top level diagram for the essential model is shown in Figure 53; there are many levels of detail below this and an accompanying document describing the various functions.

2.9.2 Develop concepts

In this set of activities we identify the internal needs of the data management system and the impacts of external requirements and limitations, and establish the criteria for selecting between alternative implementations.

2.9.2.1 Model data volume and rate

SNAP can generate 12 Gbits of exposure data in 20 seconds every 300 seconds when it is operating in optical photometry mode. This instantaneous data rate must be memory buffered to match any reasonable telemetry bandwidth. Lossless compression can be applied to the data before storage or algorithmic processing of multiple images can be performed to reduce the size of memory buffer required.

2.9.2.2 Study memory/CPU/telemetry impacts

SNAP images are formed by adding four or more exposures. The exposures are cross-correlated to remove contamination by cosmic rays. There are two approaches on where to combine the exposures into cosmic-cleansed images, on the spacecraft or on the ground. Co-adding exposures on the ground would require very little satellite CPU resources and software, assuming data compression is done in hardware. But large memories and high telemetry rates are certainly required. Co-adding images in the satellite can reduce the telemetry rate requirements by a factor of four but requires sophisticated on-board software operating in several CPUs. For example, calibration codes would have to be executed in space since up-link rates are likely limited to a few tens of kilobits per second and transferring multi-Gbyte files is impractical. Another restriction is that only one cosmic ray cleanup algorithm can be used and this must be perfectly tuned prior to launch. Such code would also be complicated by the need to dither image placement on the imager for each exposure.

We currently favor transmission of all exposures without processing other than compression. We also believe that without complex on-board processing it will be easier to design the electronics and software.

2.9.2.3 Develop data processing concepts

Here we need to compare the different data processing paths that we might execute in the satellite and understand their impact on the above. The metric to be used includes memory size, number of CPUs, quantity of software, telemetry rate, doing no harm to the data, *inter alia*.

2.9.2.4 Document SNAP instrument control

SNAP instrument control can be viewed from the top down or from the bottom up. Let's pursue the former course here. On the ground, an observation command set will be assembled to direct the instruments' autonomous activity for a period of time, a day, a week, or some other period to be worked out. The details of what needs to be accommodated in this command set needs to be worked through with the ground station concept team. Also, where in the satellite these instructions are executed needs to be negotiated between the spacecraft and instrument concept teams. Since the instruments will be developed in parallel at more than one site, weight should be given to a concept that allows multiple, local development efforts that are easily integrated into an instrument package very late in the construction phase.

To execute an observation program, the instruments are cycled through various modes of operation, for example, electronics configuration, sequencing shutters and filters, reading out detectors, flashing calibration lamps, erasing persistent images, and more. There will be health and environmental monitors in the instruments to insure data quality. Under this task we need to document instrument control and monitor needs. An early determination of these needs can allow us time to develop a common physical and logical interface to both the data collection system and the control system for all the instruments.

The information transferred across the interface between the instruments and the spacecraft control and telemetry system needs to be defined. Clearly the observation command set must pass from the telemetry system to the spacecraft control and then to the instrument control unit. If an instrument control CPU is executing the observation commands, it needs to communicate back to the spacecraft control with information such as the desired pointing direction. An area requiring special attention is the how the fine star guider data are handled to select stars and provide high rate updates to the satellite attitude control system.

2.9.3 Perform implementation research

In this set of activities we explore potential physical implementation of the data management system that match with a still fluid set of requirements.

2.9.3.1 <u>Survey available hardware/interfaces</u>

It is undesirable to develop a new untried data acquisition system for SNAP unless absolutely required. A survey of existing space memory, CPUs, and architectures needs to be performed, including consultation with spacecraft vendors and memory system vendors.

For instrument control and monitoring, we will look for existing protocols and physical implementations and study their suitability for SNAP.

2.9.3.2 <u>Survey of existing/proposed systems</u>

SNAP is not alone in learning how to deal with large satellite data sets. We will spend time to research what has been done in other satellites and what is being considered for the future. There is a wealth of information being generated by the NGST on this issue.

For compression studies, a variety of algorithms are available. One that is much discussed for space imaging is the Rice algorithm; it is available in both software and hardware forms. For space images, compression efficiency is often determined by read noise. We can use dark images from our CCD test stand to measure how well they compress. Access to 16-bit unprocessed Hubble images will also be useful.

2.9.4 Develop requirements

At the end of the R&D phase we will have made the decision on the extent of on-board data processing we require based on tradeoffs of CPU versus memory versus telemetry. Implicit in this is the choice of a data compression scheme.

A requirements document capturing all the interfaces to instrument data and control, spacecraft control and telemetry, and ground station instrument control messages will be generated. A block diagram of the architecture will be developed showing these interdependencies and data rates.

2.9.5 CDR planning

The deliverable at the end of R&D is a cost and schedule for the engineering and construction of the on-board data management electronics. This will be supported with a requirements document and block conceptual design.

2.9.6 Planning for long lead procurements

At this time, no long lead procurements are anticipated.

2.9.7 R&D deliverables

Table 13 highlights deliverables generated during the R&D effort.

Table 13. DAQ deliverables schedule.

Deliverable	Completion
Requirements document	Jul 2003
System conceptual design with block diagram	Feb 2004
Construction cost and schedule	Jul 2004

2.9.8 Risk assessment

One of the purposes of this research is to minimize the probability that custom solutions will need to be designed and qualified during the construction phase. Our architecture will be strongly influenced by available commercial or other space-proven hardware.

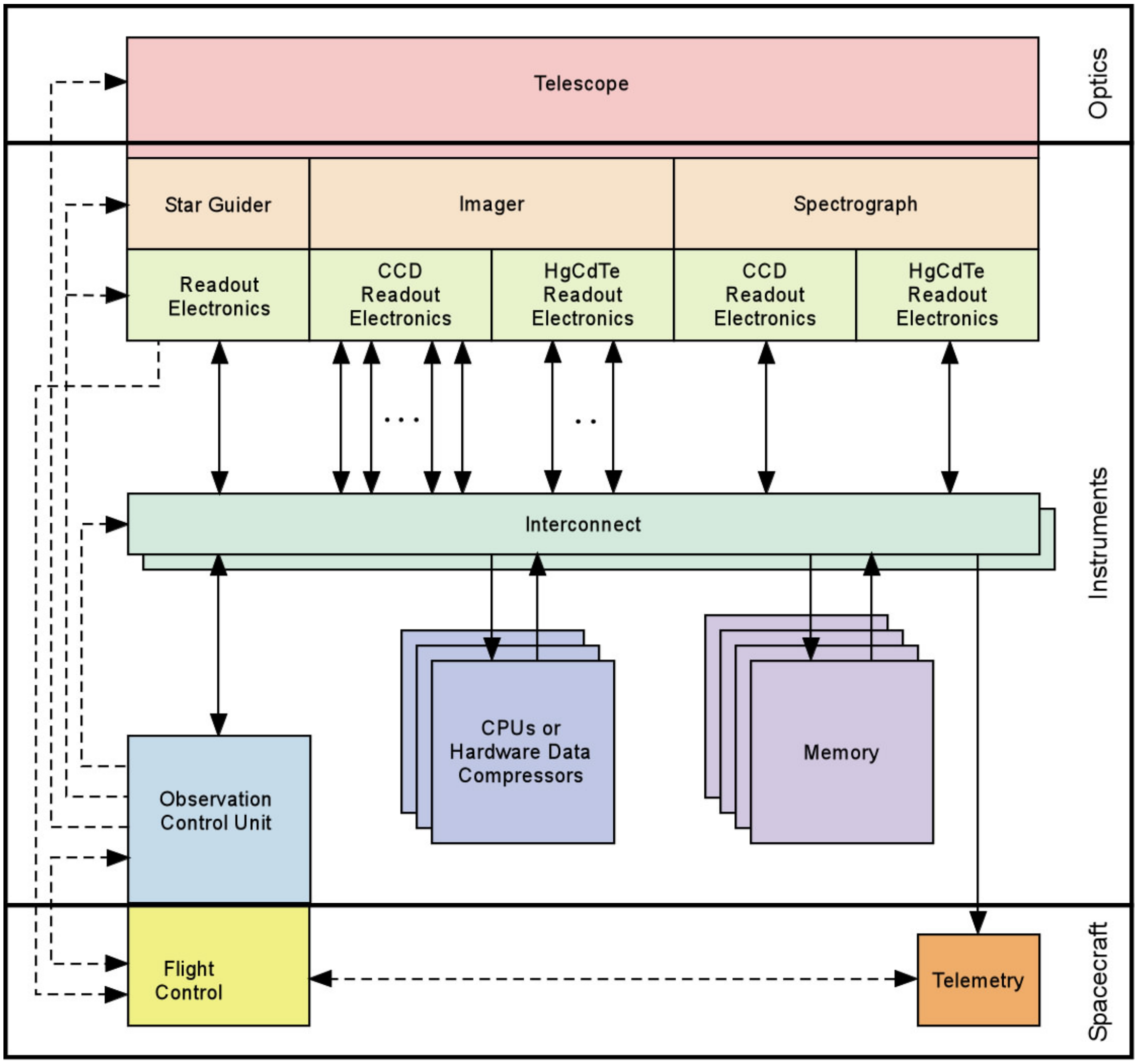


Figure 52. Preliminary concept for instrument data acquisition and control.

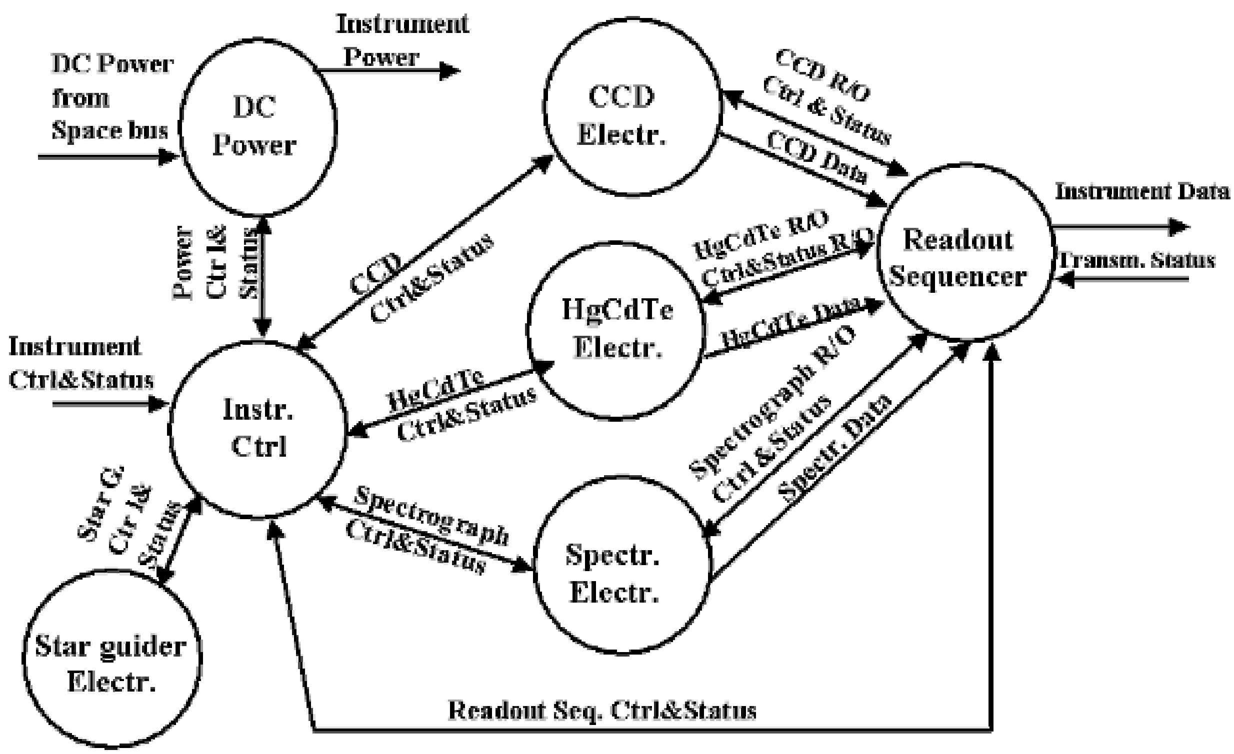


Figure 53. The top level diagram of the essential model. All the functions of the SNAP electronics and data acquisition are captured in this model.

2.10 Front-end Electronics

The SNAP instrument electronics will perform analog signal processing, digitization, clock, control, bias generation, monitoring, and data acquisition for the wide-field camera, spectrograph and star-guiders. A concept for the electronics chain has been developed to read out the SNAP CCD and the Rockwell HgCdTe sensor. A block diagram of the readout electronics is shown in Figure 54. The major blocks per sensor are: 1) DC voltage generation, 2) clock generation, 3) correlated double sampler, 4) analog to digital converter, 5) temperature monitoring, 6) interface to instrument configuration bus, and 7) interface to image data buffer. A similar chain is required for the HgCdTe sensor readout.

Due to the large number of sensors and the limited power, weight and volume that can be accommodated by the spacecraft, the conceptual design has evolved towards miniaturization of the front-end electronics by means of application-specific integrated circuits (ASICs). While the requirements for the front-end circuits are within the realm of similar custom ICs that have been designed for high-energy physics experiments, any ASIC development effort that combines analog and digital processing invokes some schedule and technical risk. The electronics R&D program emphasizes an early R&D effort on the front-end ASICs in order to mitigate these. At the end of development, the parts will be brought together to build a proof-of-principle front-end system to read out both HgCdTe and CCD sensors.

The remaining electronics needed for the bias, control and clock generation, power regulation and data compression are likely to be based on commercially available parts or simple VHDL digital circuits that involve much less risk. R&D in this area described in the DAQ section will focus mainly on the requirements and conceptual design. Power consumption, thermal requirements, and physical volume are needed inputs for the spacecraft design, and will be described in an interface control document.

The SNAP instrument front-end electronics must address several challenges, including very low noise, large dynamic range, low power consumption and radiation tolerance. In addition it must be robust and reliable enough for operation in space. Conventional implementations relying solely on discrete parts have been surveyed and will exceed any reasonable satellite power budget. Commercially available integrated circuits (ASICs) have also been considered; there are none currently available that meet SNAP requirements, but Rockwell is developing an ASIC that may meet SNAP requirements for HgCdTe readout. For the CCD readout we plan to develop a custom integrated circuit; with minor modifications it will meet the requirements for HgCdTe readout as well and functions as a backup in case the Rockwell IC does not meet our requirements or schedule. Both the LBNL and French groups in SNAP have extensive experience with custom integrated circuit (IC) design, including the design of radiation-tolerant circuits in commercially available deep submicron CMOS. Operation of the readout electronics at cold temperatures is an additional area we are interested in researching. If the electronics can be operated at cryogenic temperatures, the front-end may be located very close to the cold focal plane, eliminating long cable runs for small analog signals, reducing the cable plant and reducing the complexity of the overall thermal, mechanical and electrical design

2.10.1 Detector signal characteristics

The SNAP satellite instrumentation suite will use scientific grade silicon CCDs and HgCdTe sensors. The output characteristics of several manufacturers' sensors are shown in Table 14. Read noise is for a 50 kpixel/sec readout rate. An important difference between traditional CCD devices and the near-infrared sensitive HgCdTe sensors is that HgCdTe can be non-destructively read out and multiple samples can be used to reduce the read noise.

Table 14. Sample characteristics of CCD and HgCdTe devices.

Manufacturer	**Model**	**Gain** μ**V/*e***	**Well depth ke**	**Read noise *e***	**Polarity**
LBNL	SNAP	3.5	130	2.0	positive
SITe	SI-424A	1.0 – 1.3	150 – 200	5 – 7	negative
EEV	CCD44-82	4.5 – 6.0	200	2.5	negative
Rockwell HgCdTe	Hawaii 2	2 3 – 6.0	100	(10-17)/$\sqrt{N}$	negative

The output structure of a CCD is shown in Figure 55. A floating diffusion capacitor is reset to a reference level before each pixel is read out. The reset voltage level is uncertain by the kTC noise of the reset transistor. The pixel charge is then transferred onto the capacitor and added to the uncertain reset level. The correlated double sampler (CDS) technique is used to remove the reset level; a sample of output signal after reset is subtracted from the output generated after the pixel charge transfer. This can be done in digital or analog mode. The read noise is a function of the pixel read rate; for an LBNL CCD, the post-CDS read noise can be as low as 2 *e* at a 50 kpixel/s sample rate (Figure 56) using a dual-slope integration CDS. For the imager at visible wavelengths, the requirements are a read noise of 4 e- or less and a total readout period of 20 s or less. For a 3.5k x 3.5k CCD, 8 readout nodes are planned, each operating at 100 kpixel/s. This results in a readout period of 15 s at 100 kpixel/s with a sample time of 5 µs, corresponding to 3 e- read noise. The spectrograph has more stringent requirements on read noise, but can afford longer sampling times since it has fewer pixels per device.

The well depth of a pixel is the amount of charge than can be collected before blooming into adjacent pixels. For SNAP, the CCD well depth will be of order 130,000 *e-* and typical linearities are sub-1%. The range of signal levels of interest is from the noise floor of 2 e- to the full well-depth, corresponding to a voltage range of 7 μV to 455 mV. This is a 16-bit dynamic range.

CCDs require several clocks to move the pixel charge for readout. A set of clocks performs a parallel shift of pixel columns into a serial shift register. The voltage swings of the clocks are approximately 10 V, the parallel clock capacitances are ~20 nF, and the serial clock capacitances are ~10 pF. The drain voltages for the output FETs are 20–25 V and the depletion voltage is 30–80 V.

For HgCdTe devices, the reset and signal sample times are temporally disjoint and the correlated double sample operation is performed digitally. The pixels can be non-destructively read. For example, the pixels are reset, the reset levels are digitized and stored, and after an exposure period the pixels are digitized again. A digital subtraction of the two arrays accomplishes the CDS function. Other noise reduction techniques, multiple Fowler sampling and up-the-ramp sampling are also possible in the digital domain. Multiple Fowler sampling does many consecutive reads after reset and after exposure to statistically reduce the read noise. Up-the-ramp sampling makes periodic, continuous reads of the pixels during the exposure. This also reduces the impact of read noise and can detect cosmic ray charge deposition. The readout clocks for these devices are CMOS logic levels and the maximum output signal is 500 mV.

Rockwell HgCdTe devices are under consideration for the scientific instrumentation suite for NGST, and Rockwell is developing a custom integrated circuit for HgCdTe readout. This development effort is proprietary, and the specifications and performance are not yet available. We will follow this effort and take advantage of it for SNAP if it meets our requirements. At the same time our own development effort will maintain compatibility with both silicon CCDs and HgCdTe devices, because the additional engineering required is minimal and we can use the CCD readout as a back-up for HgCdTe readout if the Rockwell IC proves to be unsuitable or unavailable. Another option is to contract with Rockwell to modify their readout ASIC to meet SNAP requirements.

2.10.1.1 Progress in the Past Year

The correlated double sampler was identified as an item that would benefit from an ASIC implementation to meet the stringent analog processing requirements, reduce power and parts count, and achieve the required level of radiation tolerance. A preliminary requirements document for this sub-component was completed in October 2000. The operating characteristics of a variety of CCDs and HgCdTe devices have been surveyed, and it is possible to establish requirements for an electronics readout system that is compatible with all of them. The CDS requirements document addresses the following items:

- Input signal characteristics.
- Correlated double sampler specifications
- Global specifications (dynamic range, linearity, cross talk, power, PSRR, temperature, radiation tolerance).
- Packaging

Based on these requirements, a CDS design was implemented by the French group for the DMILL radiation hard process that we access through a European multi-project organization. The fabrication was completed in March 2001 and tested. There was a design problem, but the circuit was operational and has been tested. Noise measurements were performed and showed somewhat worse performance than expected from simulation.

In the meantime, uncertainties regarding the future of the DMILL process have prompted us to consider other technologies. We have surveyed ten submicron and deep-submicron CMOS technologies and considered a variety of characteristics including minimum feature size, noise performance, matching characteristics, simulation tools, radiation tolerance data, multi-project wafer accessibility, and anticipated process longevity. The latter is of particular importance because this R&D is early with respect to the SNAP construction phase.

In order to understand the impact of the technology selection on the noise performance of the final circuit, we carried out noise simulations for different process parameters in several different signal processing methods. The preliminary conclusion of this study was that a differential averaging technique has the best performance. With a gain stage in front of the integrator, the dominant noise source will be the CCD itself with a minor (<10%) contribution from the signal processing. This conclusion did not depend strongly on the details of the process-dependent noise parameters, so we concluded that noise performance was in fact not the chief deciding factor in the technology selection.

Based on our survey of available IC processes, we selected two processes for further study: TSMC 0.25 μm and UMC 0.18 μm. Both meet our requirements, are expected to be available for several more years, and are accessible via multi-project wafer services. TSMC has the highest volume of any semiconductor fabricator in the world. Because LBNL has already designed ICs in this process we already have design tools, fully designed circuit modules including radiation-hard transistor layouts, and access to test parts.

We obtained a test chip for the TSMC 0.25 μm process and used it to carry out cold temperature tests on a variety of transistors. These measurements demonstrated good agreement between simulation and data for the threshold voltage dependence, as shown in Figure 57. We were also able to reproduce the electron mobility over the range 150–300 K by tuning one of the simulation model parameters. Very similar results were obtained in another process (IBM

0.25 μm), giving us additional confidence that deep submicron CMOS circuits can be designed for operation at both room temperature and 140 K if sufficient headroom is allowed for the expected shifts in threshold voltage.

We are now in process of reviewing and revising the requirements document in preparation for the design of a test chip that will contain a CDS circuit and a variety of smaller test devices. The French and LBNL groups are working closely. The LBNL group has targeted a submission to TSMC 0.25 μm via MOSIS in the fall of 2002. The French group will target a submission to UMC 0.18 μm via Europractice.

2.10.2 Finalize requirements

The requirements document for the SNAP instrument electronics must consider both CCDs and HgCdTe sensors and their use in both the wide-field imager and the spectrograph. While there will be some small differences in requirements among these use cases, the overall goal to maintain compatibility with all sensor types in SNAP is a primary requirement for the electronics. Our work so far indicates that a modest flexibility is achievable to provide this compatibility with a small extra effort. The requirements document for the SNAP instrument electronics will discuss requirements for both CCD and HgCdTe operation, including:

- On-detector electronics.
- Analog signal processing.
- DC voltages and their cycling.
- Clock parameters such as levels and shapes.
- Clock sequencer and modes of operation.
- ADC interface.
- Data processor/memory interface.
- Local resource configuration and control.
- Overall power and control.

Once assembled, the draft requirements document must be formally reviewed and finalized.

2.10.3 Develop conceptual design

After agreement to the requirements document, the system architecture will be developed and detailed in a block diagram. A good deal of engineering time will be spent on this high level design to make trades between ASIC and conventional parts implementations. The use of ASICs is motivated by at least three important concerns: 1) power consumption, 2) size and weight of the whole system, and 3) reliability. Experience in high energy physics has shown that the use of ASICs for readout of a large number of detector channels can reduce the size of the front-end electronics and the needed power. Large standing currents to load and unload highly capacitive interconnect media such as copper tracks or wire bonds on hybrids or printed circuit boards can be reduced and power saved. As an order of magnitude, the stray capacitance to ground of an interconnect between two chips a distance one centimeter apart on a multi-layer PCB is of the order of 1 pF. This is to be compared to 10 fF for a one-millimeter interconnect on an ASIC. As another example, the CFHT MegaCam front-end electronics built with discrete components dissipates 7.5 W per CCD, to be compared to 0.50 W as planned using ASICs.

So far, we have concluded that at least one ASIC will be required, to perform the precision analog processing of the correlated double sampling. Another function that may benefit from ASIC implementation is the ADC, if commercial ADCs do not meet SNAP requirements. The suitability of commercial ADCs will depend on the final optimization of the warm/cold boundary in the electronic readout chain. The CCD controller is another candidate, though commercial solutions or FPGAs may also provide a solution. The generation of clock waveforms and control voltages for the CCD and HgCdTe sensors requires high voltage, limiting the choices in integrated circuit technology and posing more risk. We will consider both discrete and ASIC solutions for this aspect.

Another important aspect of the conceptual design is the location of the electronics. If the front-end electronics can be operated at the same temperature as the cold focal plane, 140 K, it can be located very near to the sensors. This will reduce the cable plant and eliminate the need to run sensitive analog signals over long cables. This in turn will impact the signal buffering and drivers and the overall shielding and grounding design. Our initial tests of transistors at cold temperatures are quite promising, as discussed above. A final decision must await cold testing of a CDS test chip in one of our target technologies.

In the process of developing a conceptual design it is important to maintain fallback options that can be exercised in the event that R&D does not succeed in meeting the target goals. We have a number of fallback options for the SNAP electronics. For example, if we fail to demonstrate successful cold operation of the front-end electronics, the fallback option is to remove it to the warm area. Similarly if the power consumption of the front-end electronics cannot be reduced to a level consistent with the thermal constraints on the focal plane, we will either remove some functionality to the warm area, or explore more sophisticated cooling techniques that can handle increased power. It is also important to have a fallback in case the Rockwell ASIC for the HgCdTe readout is unsuccessful or fails to meet our requirements. In the former case we would adapt our CCD ASIC development for readout of the HgCdTe sensors; in the latter case it we would negotiate with Rockwell to see if they could develop a SNAP-specific ASIC that did meet all of our requirements. We also have two options for the ADC: first we will try to find a suitable commercial part; and if that is unsuccessful we will adopt an existing LBNL design for a 12-bit ADC by employing a multi-range input stage.

2.10.4 Development of system components

After the completion of the system block diagram and the decision on implementing each functional block, technology selection, design, fabrication, and test of the ASICs can begin. All the electronics components must survive a lifetime radiation dose of 10–50 kRad. In addition, components must demonstrate acceptable levels of immunity to single event upset (SEU) and single event latchup (SEL). The number of IC processes available is therefore limited. Design kits should provide reliable semi-conductor devices models after irradiation. As well, the test plans will incorporate tests after irradiation. In parallel with hands-on R&D for the front-end ASIC, we will develop a conceptual design for the more conventional aspects of the electronics as a basis for the CDR cost and schedule estimates.

2.10.4.1 Develop CDS ASIC

Two deep submicron CMOS processes have been identified for the CDS chip, TSMC 0.25 µm and UMC 0.18 µm. The LBNL group will access the TSMC process through MOSIS and the French group will access the UMC process through Europractice. We will share all of our simulation and design work and develop common testing procedures. The IBM 0.25 µm process is also a backup for TSMC 0.25 µm should we need it. An important consideration in selecting among the available processes was the maximum usable voltage that impacts the achievable dynamic range. At the other end, thermal and $1/f^n$ noise have to be kept small compared to the CCD readout. We are pursuing these two technologies through two design iterations. Low noise performance is absolutely critical for extracting the most information from the CCDs and HgCdTe devices. In addition, the electronics must be radiation tolerant and it is desirable to operate it at low temperature. Our testing plan will include irradiation and operation at cryogenic temperatures. A second iteration of the CDS chip is planned for submission in mid-2003. This iteration will likely include an integrated ADC based on an existing LBNL design for a 12-bit Wilkinson ADC.

2.10.4.2 Procure and test Rockwell HgCdTe ASIC

Rockwell is developing an ASIC for HgCdTe readout for NASA. The first parts are of the Rockwell ASIC are due October 2002. We are in contact with Rockwell and will follow this development effort closely; however Rockwell has not shared the detailed specifications with us. If the first submission is successful we will attempt to obtain parts from Rockwell to carry out our own tests. This work would be done in collaboration with the University of Michigan group who will be acquiring HgCdTe sensors and testing them. If the Rockwell ASIC does not meet SNAP requirements it is also possible that we could contract with Rockwell to submit a modified version that would be suitable for SNAP. They have provided us with an estimate for this type of work and we carry this as a contingency.

In the event that the Rockwell ASIC does not meet our requirements, we have a fallback option to use a modified version of our CCD readout ASIC. The requirements for HgCdTe readout are not very different from those for CCD readout and we are keeping this possibility in mind as we specify and design the CDS test chip.

The goal of the R&D period for HgCdTe readout is to demonstrate a complete readout chain from the sensor to the digitization of the data that meets all of SNAP's requirements, whether it be based on the Rockwell ASIC or our own CDS chip. This includes testing at low temperature and irradiation.

2.10.5 Design prototype system

To be able to test the ASICs several parts of the readout system that will probably use conventional technologies need to be designed and built. For example, the sensors will be connected to the readout electronics with some sort of cable. Present thinking is that this will be a flex circuit that penetrates the focal plane. There will inevitably be some commodity parts surrounding the ASICs on the readout cards. These will have to be selected to meet space environment requirements. A survey of commercial parts will be undertaken, one or two parts selected, and a program to certify them for space flight will be performed, either in-house or commercially.

2.10.6 Perform system testing

The completion dates we have scheduled for the fabrication of ASICs follow from submission dates for multi-project prototyping services. A first iteration of the CDS ASIC will be submitted in November 2002. Printed circuit boards and computer interfacing and test software can be developed ahead of time, leveraging the test environments developed for testing the individual components. Stand-alone testing is completed in early 2003. The second iteration of the CDS test chip, incorporating an ADC, is scheduled to be tested and available for system tests in December 2003, when it will be connected to a CCD in the LBNL CCD laboratory.

2.10.7 CDR planning

A major deliverable at the end of R&D is a cost and schedule for the construction of the front-end electronics. The development of a comprehensive requirements document early in the process will help insure that all the necessary items are identified. The program of ASIC development and conventional parts selection will establish the production costs for these items. We note that ASIC development may not be entirely complete on the time scale of CDR but this does not preclude costing production parts on the basis of one or two prototype runs. The cost and schedule for construction will be developed during the last six months of R&D using as input the actual material costs and labor efforts required during prototyping of the components described above.

2.10.8 Planning for long lead procurements

It is likely that at the time of CDR we would seek approval to move ahead with the procurement of the ASICs as fast as possible, subject to the state of the prototype development. There are several reasons for this. One, ASIC fabrication runs have an associated risk of failure where months of delay can be incurred while parts are re-fabricated. Two, a chosen semiconductor technology may not have a long lifetime and therefore may no longer be available if there is a large gap between development and production. Three, an engineering team will have been assembled during the design and prototyping stage and continuity of personnel and familiarity can be lost and additional engineering costs incurred if parts are not ordered and tested in a timely manner.

2.10.9 R&D deliverables

Table 15 lists deliverables generated during the R&D effort.

Table 15. Frontend electronics deliverables schedule.

Deliverable	**Completion**
CDS Requirements document	Jul 2002
Test results from first CDS ASIC	Feb 2003
Procure and test Rockwell ASIC	Apr 2003
Clock & control conceptual design	Oct 2003
Test results from second CDS ASIC	Dec 2003
Ground, shield conceptual design	Nov 2003
DAQ conceptual design	Feb 2004
Prototype CCD R/O system test	May 2004
Prototype HgCdTe R/O system test	May 2004
Construction cost and schedule	Jul 2004

2.10.10 Risk assessment

There are risks associated with developing custom ICs. Design iterations may be required. Fabrications may fail or be delayed. But the potential costs are time delays. Success can eventually be achieved. ASIC development for SNAP is actually itself a risk mitigation. Reading out 900 sensor channels with conventional electronics is not a viable option from a satellite power standpoint. We are also trying to dramatically reduce the number of parts that need to be tested for space environment by using ASICs.

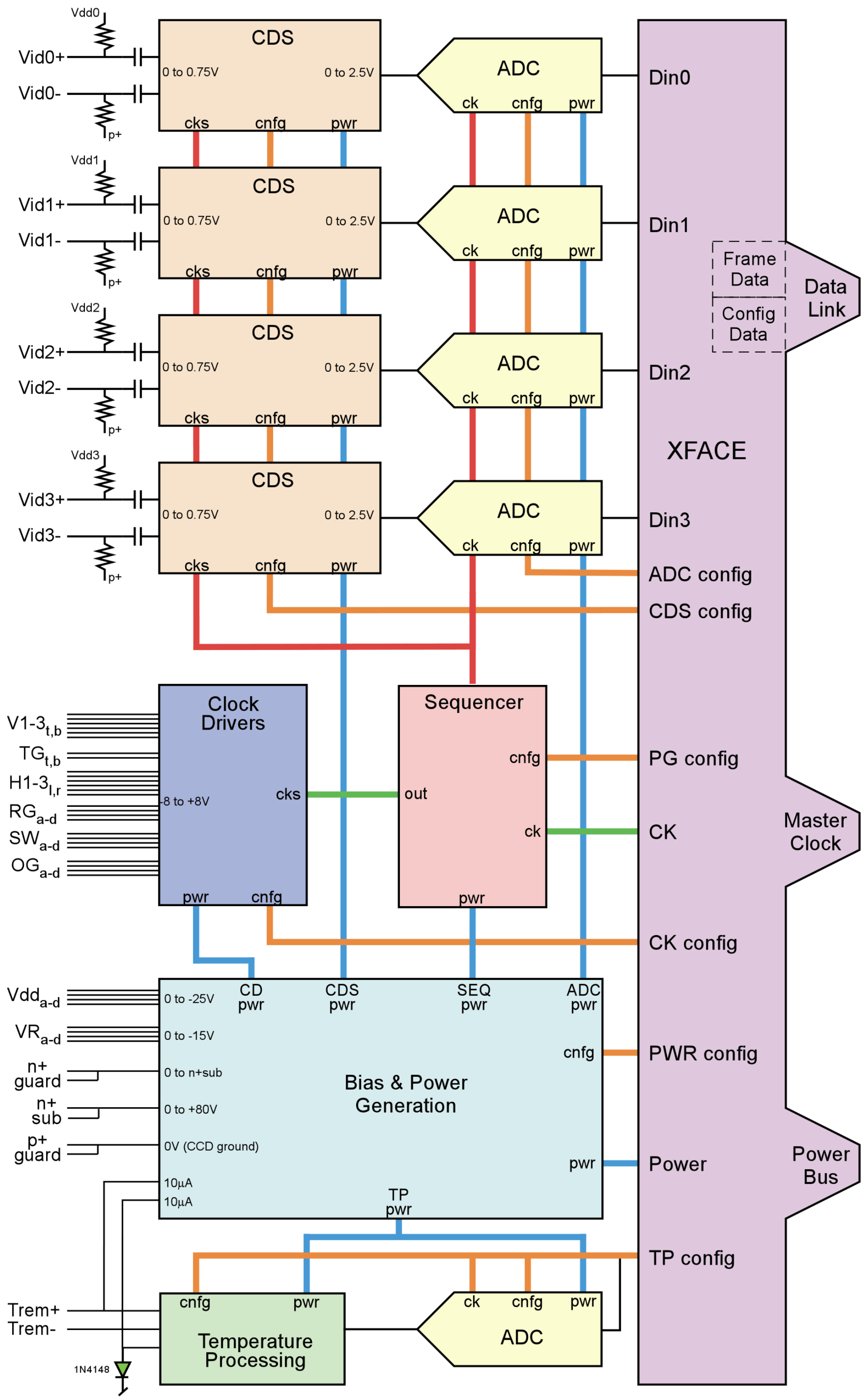
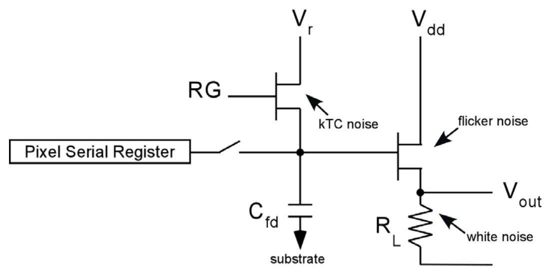


Figure 54. Preliminary concept for CCD readout electronics.



Reset kTC noise is ~150 e^-.
Read noise is ~2 e^- at 50k sample rate.
Gain is ~6.0 $\mu V/e^-$.
R_L is 5-10kΩ.
Well depth is ~120 ke^-.
$1/g_m$ is 3-5 kΩ at 1 mA and 10 V.

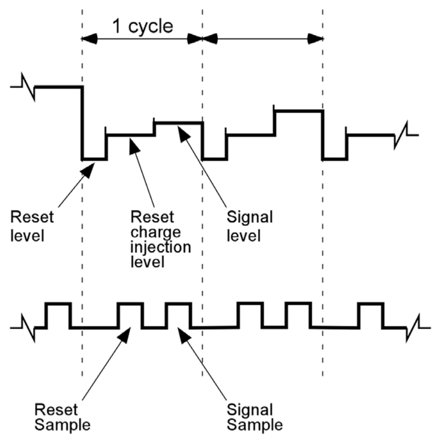


Figure 55. CCD output structure and waveforms.

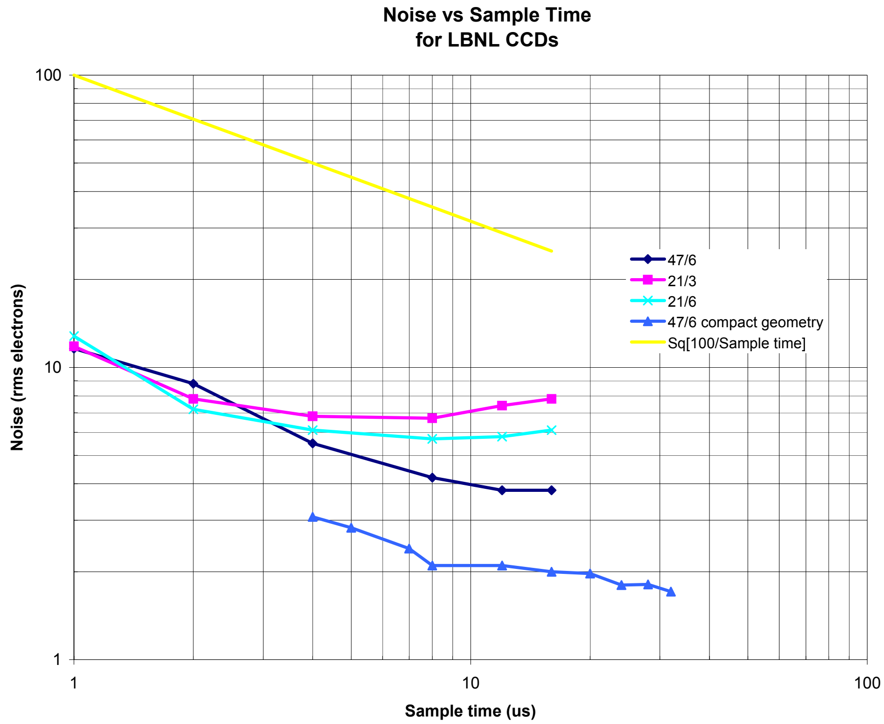


Figure 56. Post-CDS readnoise measurement for LBNL CCDs.

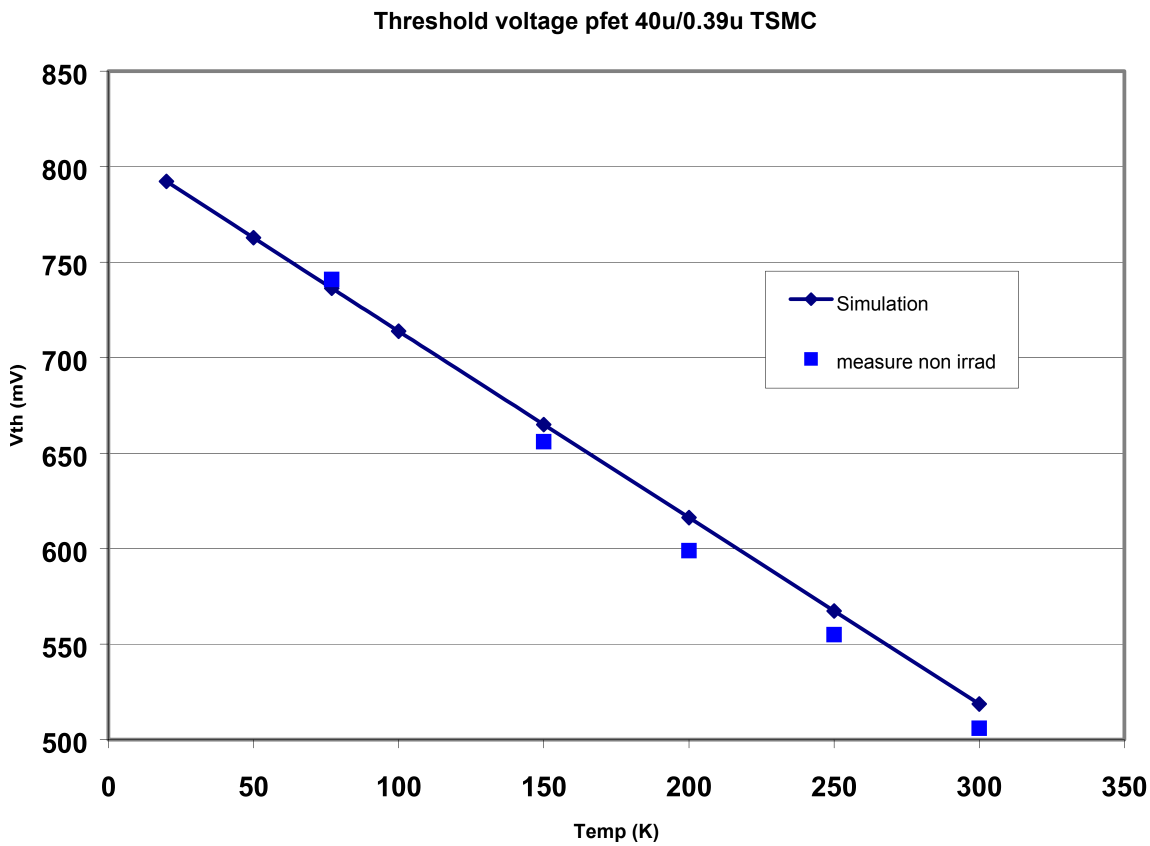


Figure 57. Voltage threshold dependence of TSMC 0.25 µm process for PMOS transistor.

2.11 Mechanical systems

In this we describe the mechanical components and activities during the R&D phase surrounding them. There is little R&D effort required. Mainly, concepts and interfaces with the telescope and spacecraft are developed. This is reflected in the cooperative work of engineering from the satellite system engineering team and the instrument.

2.11.1 Shutter

SNAP will have a mechanical shutter located behind the telescope folding mirror. A concept is show in Figure 58. It provides multiple functions: normal exposures of well determined time, fast exposures for calibration on bright objects, a flat for calibration illumination. The effort in this area is mainly conceptual development to a level sufficient to do costing and scheduling. One area of research is a survey of potential drive mechanisms that can be used in a failsafe manner.

During the R&D phase, the shutter concept team will need to interact with the calibration team to understand the minimum exposure time required and achievable. Joint activities with the System Engineering group will be budgeting space and mass and insuring that any net momentum disturbance during shutter actuation can be accommodated by the spacecraft attitude control system,

2.11.2 Shield

Following the shutter, the optical beam expands to the focal plane inside a container we will simply refer to as the shield. This object must accomplish several things:

- Isolate the focal plane from thermal radiation from the warm satellite.
- Block stray light from impinging on the focal plane.
- Attenuate the cosmic ray flux as much as is practical.
- Absorb backscattered light from the surface of the sensors and their mounts.

The role of the shield as a cosmic ray attenuator makes this object potentially quite massive. Its placement and stability are not critical as is he case for the focal plane and a simpler attachment scheme, albeit still with thermal isolation, can be used. To begin refining the mass estimate, the R&D phase has effort for simulating charge particle attenuation using standard computer transport codes with the input of measured fluences of solar and galactic particles. The subtlety here is that the CCD images in particular are polluted more by the number of charged particles rather than the charge or energy of any one particle. A delicate balance between attenuation of primary radiation and creation of secondaries needs to be considered in this study.

2.11.3 Cold plate

An annular molybdenum plate is the primary precision mount for the imager sensors, CCDs and HgCdTe, and the spectrograph (Figure 60). The plate is operated at 140 K by connection to a passive space radiator and the temperature is regulated with heaters. The mass of the plate is supported by kinematic mounts to the telescope support structure (Figure 61). The focal plane will not have adjusters and must be stable to a couple of tens of microns in focal depth. These mounts are envisioned to also provide the thermal isolation between the warm telescope structure and the cold plate. A concept for the mounts is shown in Figure 62 that is cluster of metal balls in point contact providing both kinematic mount and thermal isolation. An R&D activity is to build a much larger unit capable of handling the SNAP focal plane mass and to measure its performance.

There will be a joint effort on concept development among the instrument mechanical engineer and mechanical and thermal engineers in the System Engineering group.

2.11.4 Cooling

The cooling source for the 140 K focal plane cold plate and its sensors is an approximately 2 m^2 plate radiating into dark space. Figure 63 shows the radiator attached to the rest of the instrument. If this radiator operates at 120 K, there will be 32 W of 140 K cooling available at the cold plate. There is no development required during the R&D phase for this device. The main effort will be interaction between the instrument and the system engineering teams to keep the electrical power dissipated by the sensors and their electronics and other thermal loads well within the 32 W budget.

The thermal linkages between the radiator and the cold plate are termed S-links. There position is shown in Figure 64. At the moment these are thought to be commercially available parts using thousands of carbon fiber strands. Such a unit is shown in Figure 65. The flexibility of these links decouples motions of the radiator from the focal plane. No R&D effort is required for these items.

2.11.5 CD1 planning

A major deliverable at the end of R&D is a cost and schedule for the construction of the mechanical components of the focal plane array.

2.11.6 Planning for long lead procurements

No long lead procurements are anticipated.

2.11.7 R&D deliverables

Table 16 lists deliverables generated during the R&D effort. Most effort in the instrument mechanical area does not commence until FY04, providing three months to complete the conceptual designs which are targeted for January 2004. Not explicitly discussed above but listed in the table is the deliver of draft interface control documents. The items discussed here have interfaces to one or more of telescope, spacecraft, and electronics. Working with the SNAP system engineering team, we will generate a draft set of ICDs at the end of the R&D phase.

Table 16. Mechanical systems deliverable dates.

Deliverable	**Completion**
Shutter conceptual design	Jan 2004
Shield conceptual design	Jan 2004
Shield refined mass estimate	Apr 2004
Cold plate conceptual design	Jan 2004
Cold plate mount prototype construction and characterization	Jan 2004
Radiator concept	Jan 2004
Radiator-S-link-cold plate connection conceptual	Jan 2004
Draft interface documents	Jul 2004
Integrated construction cost and schedule	Jul 2004

2.11.8 Risk assessment

We do not identify any high risk issues associated with developing the mechanical components described above.

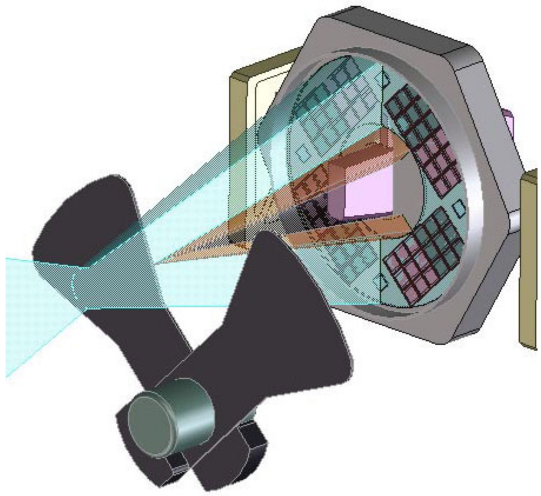


Figure 58. Shutter concept.

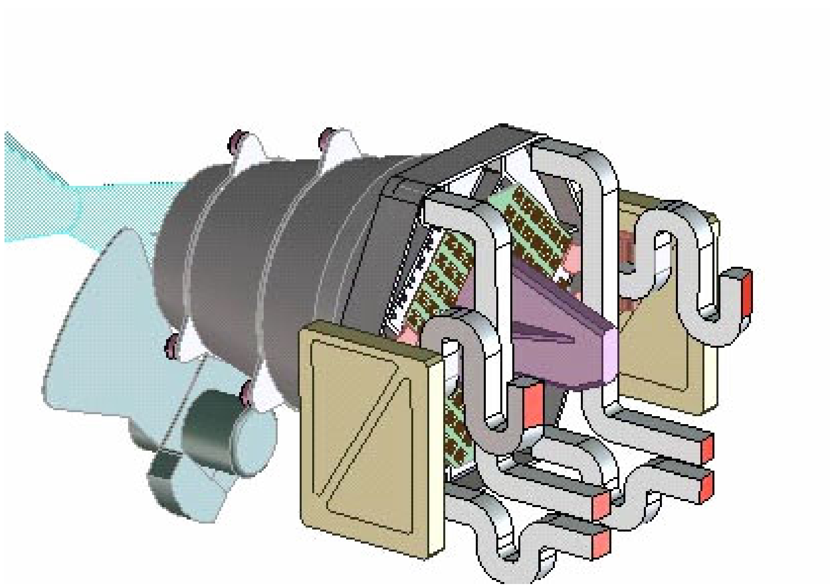


Figure 59. The shield is the conical object between the shutter and the focal plane.

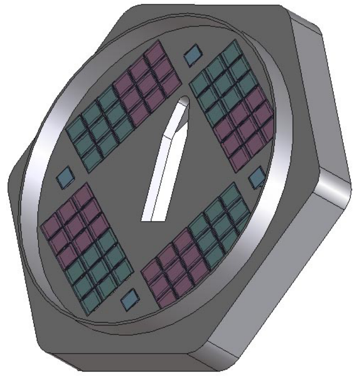


Figure 60. A front view of the cold plate showing CCD and HgCdTe sensors mounted.

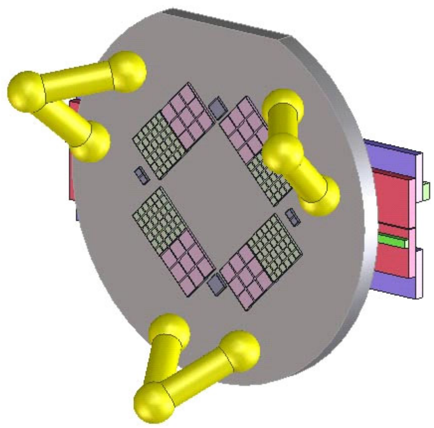


Figure 61. Concept of bi-pod mounts providing kinematic support of the cold plate from the telescope structure.

Figure 62. Candidate concept for the kinematic/thermal-isolation mount of the cold plate to the telescope.

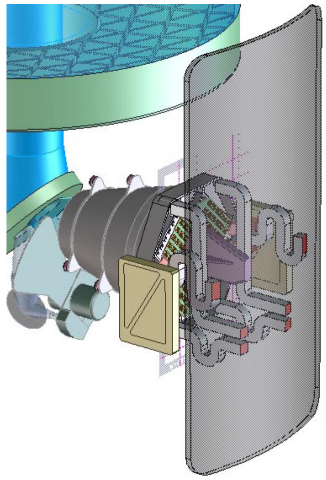


Figure 63. View of the space thermal radiator relative to the rest of the instrument.

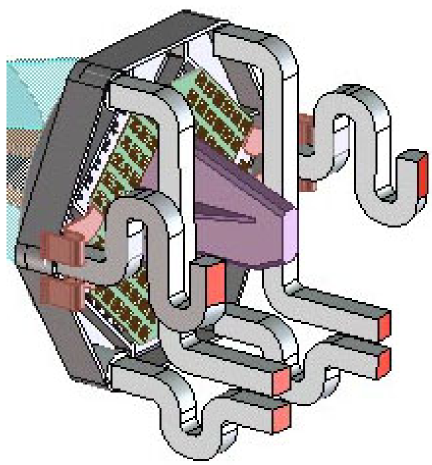


Figure 64. Thermal conducting S-links showing their attachment to the cold plate. The near ends of the links are attached to the radiator.

Figure 65. Example of commercially available S-links comprised of tens of thousands of flexible carbon fibers.

Section 3. Calibration R&D plan

The R&D tasks associated with SNAP Calibration are driven by the need to prepare a thorough specification of the spectrophotometric calibration (absolute color calibration), the data processing pipeline (calibration pipeline), the instrument calibration requirements, and the interfaces between the calibration team and the instrument and ground systems teams. This specification will in turn permit the development of a sound plan for achieving the required color calibration precision.

1. Our requirements will be written with careful consultation with scientists (astrophysicists, solar physicists, space scientists) having established credentials in the various aspects of calibration at research institutions and at the National Institute of Standards and Technology (NIST) . Toward this end we will continue to form a calibration team whose cumulative experience is appropriate for a project of the scale of SNAP.

2. Absolute Color Calibration: Our requirements will be carefully prioritized with respect to potential tradeoffs that control the calibration error budget. We have identified several possible routes and we anticipate that as further constraints are better understood, our trade studies will allow us to properly assess the different methods and select the one best suited for the SNAP science.

3. Calibration Pipeline: Our specifications for a calibration database to deliver the required science will be refined. The pipeline produces the calibration products used to process each data image: a) dark and bias frames to remove dark current and pedestal effects; b) flat fields to control for the high-frequency, pixel to pixel variations in response; and c) photometric zeropoint and spectrophotometric references to determine the flux and colors. These calibration products must be monitored during operation. During the R&D phase we will develop, in concert with the instrumentation groups, diagnostic metrics of system behaviors.

4. Instrument Calibration: By the end of the R&D phase we will have developed a detailed calibration plan tracing all steps in the calibration process for each instrument. Each step will include the procedures and the means to validate those procedures.

Since the methodology for each aspect of calibration is already established, we do not anticipate having to engage in basic prototyping. Both instrument calibration and calibration pipelines have been established by past, present, and future space missions, *e.g.,* International Ultraviolet Explorer (IUE), Hubble Space Telescope (HST), Chandra X-ray Observatory, and the Space InfraRed

Telescope Facility (SIRTF). However, the R&D phase provides the needed time span in which to conduct concept development and to refine our requirements for the more demanding calibration component: the absolute color calibration.

3.1 Requirements overview

Here we present a preliminary list of the requirements that will be specified during the R&D phase. The main result of our R&D study is a detailed plan for calibration which will be carefully reviewed by all members of the calibration working group prior to the scheduled CDR project milestones.

1. Instrument calibration:
   - in flight and ground methods
   - performance vs. environment

2. Calibration Pipeline:
   - quality of flat-fields
   - frequency of calibration observations
   - diagnostics to monitor temporal changes
   - diagnostics to monitor frequency shifts in response
   - impact of calibration hardware (*e.g.,* lamps, shutter) on instrument design

3. Absolute Color Calibration:
   - minimum error budget
   - minimum transfer errors from primary source to target object
   - maximum allowed systematic errors in the optical
   - maximum allowed systematic errors in the near infrared

4. Other Issues
   - primary source selection: sun, NIST blackbody
   - secondary source (stars) selection: spectral types

3.2 Calibration R&D trade studies

3.2.1 Instrument Calibration

The basic concern of calibration is to understand the instrument response to incoming light as a function of wavelength, intensity, environment and time. Options for establishing ground calibration of the instruments are end-to-end – the entire telescope – and piece-wise. This needs study. In concert with the instrument teams we will study how the science data can be used to measure and diagnose changes in in-flight performance. For example, the SNAP primary science mission will observe the same fields every four days through each filter, and thus, each of the thousands of stars in each field, this data time series may be used to monitor changes in response.

3.2.2 Calibration Pipeline

This produces the calibration products used to process each data image: dark and bias frames to remove dark current and pedestal effects, flat fields used to divide out high-frequency, pixel to pixel variations in response. Wavelength solutions determined from, *e.g.,* lamp emission spectra are applied to spectral data. The final stage is the application of the zero-point and spectrophotometric references. It is well known that accurate flat fields are important for obtaining well calibrated data. Broad spectrum lamps are typically used, though illuminating evenly a large field of view over both the optical and near infrared can impact the number and spectral range of the lamps, their location within the optical bench, shutter precision and possible diffusing surface. Alternatives to relying solely on lamps for the flat fields are using zodiacal light and/or moonlight.

3.2.3 Absolute Color Calibration

A number of trade studies have been identified. Achieving high precision in the color calibration demands precise control of systematic errors throughout the spectrophotometric calibration chain. The overall calibration of the SNAP optical and near infrared imagers and the spectrograph will be conducted through several routes. We envision employing a variety of well-studied stars, including the sun, and also performing indirect transfer calibrations that permit comparison with NIST irradiance standards to close the loop with fundamental MKS quantities. We expect that other trade studies may become necessary as our design space is explored in further detail. Here we list the known major trade alternatives along with brief explanations of their system impacts:

3.2.4 Artificial Point Sources

Precise blackbodies for irradiance measurements have been used for over thirty years to calibrate optical systems on the ground and in space. These integrating spheres are calibrated by NIST. The sun itself can also be used, *e.g.,* the Multispectral Thermal Imager project as an irradiance standard. Since our target objects are much fainter than these standards, we need to determine an optimal attenuation method suitable for the mission.

3.2.5 Platform Trade Studies

Absolute spectrophotometric calibration in the optical has been carried out on the ground for several stars, most notably Vega. HST spectrophotometric calibrations are based on models of four pure hydrogen white dwarfs from the UV to the IR and one solar analog in the IR, fixed on Landolt V band photometry. The Sloan Digital Sky Survey (SDSS) developed its own calibration program based on three primary standard stars whose absolute spectrophotometry traces back to the absolute calibration of Vega. The SDSS network of secondary standards was developed with three telescopes of aperture 0.5 m, 1.0 m and 2.5 m (the Sloan telescope itself) in order to span the required dynamic range in brightness from the bright primary standards to the faintest secondaries in the optical. The achieved precision ranges between 1.5% v′, g′, and r′ and 3% u′ and i′. SNAP is a space observatory, requiring a similar network of standard stars for the SNAP filters but with a longer wavelength reach – from 350 nm to 1700 nm. Several choices are available for establishing SNAP's own network. The first is to carry out a program from the ground. However, the atmosphere's many absorption bands in the near infrared may vitiate the reliability of the planned NIR bandpasses. The second option is a space program, perhaps using SNAP itself, which bypasses atmospheric effects. Other options include a mix of ground, space and balloon platforms. The total cost and schedule of the color calibration program depend on the choice of platform(s).

Other trade studies going hand in hand with the above concern the number of steps needed to transfer the primary calibration to the target objects, the identification of systematic errors, and the consequent carry over of systematic effects to each step. This will affect the achievable precision. We note that this depends on the platform(s) chosen as do the relative contributions of each systematic.

3.2.6 Selection of Standard Stars

Bright primary standard stars must be chosen and calibrated against NIST traceable irradiance standards. These may consist of the HST set of standard stars, but also may include others. Spectrophotometric, or color calibration, secondary standard stars covering a range of spectral types and brightness in and near the SNAP fields need to be identified and monitored to exclude variable objects.

3.2.7 Error budget

The goal of these studies is a calibration error budget, in which the magnitude and distribution of the various sources of error are correctly identified. Maintaining an overall requirement that meets the needs of the science program may require some flexibility on the individual items. This error budget will be sent for review by experienced astrophysicists.

3.3 Schedule

Calibration Plan development deliverables dates are shown in Table 17.

Table 17. Calibration Deliverables schedule.

Milestone	**Date**
Define calibration requirements	Nov 2002
Preliminary calibration error budget	May 2003
Selection of irradiance standards	June 2003
Selection of primary standard stars	June 2003
Preliminary analysis of each calibration platform	Dec 2003
Calibration Pipeline Database design	Feb 2004
Selection of standard star fields	Feb 2004
Selection of calibration platform(s)	Apr 2004
Instrument Calibration Plan	May 2004
Pipeline Interface Documents	Jun 2004
Final calibration error budget	Jul 2004
Spectrophotometric Calibration Plan	Jul 2004
Calibration CDR Document	Jul 2004

Section 4. Ground Segment R&D plan

4.1 Segment Definition

The SNAP Ground Segment consists of all ground systems required to communicate with the spacecraft to send command and control data, receive scientific and engineering data, and process all data in a timely fashion as required to operate the spacecraft and carry out the SNAP scientific mission. To accomplish these tasks, the Ground Segment is divided into Mission Operations and Science Operations.

Mission Operations will:

- Receive science observation requests from Science Operations and translate these into Command and Control sequences to be transmitted to the spacecraft.
- Up-link Command and Control data to the spacecraft
- Track the spacecraft and determine ground station availability
- Monitor spacecraft environmental and engineering parameters to ensure proper operation
- Receive and buffer scientific and engineering data during down-link at orbit perigee
- Transmit the data to Science Operations for processing and analysis

Science Operations will:

- Receive down-linked data from Mission Operations
- Verify data validity and reformat for science processing
- Apply all current calibrations as required for converting raw images into science-quality images
- Analyze the images to identify supernovae and other astronomical objects of interest
- Update the scheduler to communicate additional observation requests to Mission Ops
- Catalogue and archive the astronomical objects for further analysis
- Provide computing and software resources for simulation studies to optimize the mission plan and instrument design
- Provide computing and software resources for supporting calibration functions

4.2 Mission Operations R&D issues

The Berkeley Ground Station (BGS) located at UCB Space Sciences Laboratory currently hosts Mission Operations for the High Energy Solar Spectrographic Imager (HESSI) mission. In support of this and other missions, the Berkeley Ground Station has built up much of the infrastructure and expertise necessary for carrying out the SNAP mission. Thus for most of the Mission Ops functions for SNAP, there are no R&D issues. The few exceptions are:

- Upgrade of the antenna dish for Ka- band telemetry
    - The current BGS antenna is an 11 meter diameter dish used for S-band telemetry. To work for Ka-band, the dish surface would have to be re-worked to sub-millimeter tolerance. This will be investigated but it is likely that a new dish will be required.
- High speed data buffer and link to Science Ops at LBNL
    - The data rates for SNAP are higher and will require a new buffer and link. This will be specified during the R&D phase.
- Contingency Plan for back-up ground station(s) when BGS is down
    - Several alternate stations with Ka-band capability are possible options so a cost/availability trade study will be undertaken in the R&D phase. Data storage and delivery to LBNL will have to be understood and specified.

4.3 Science Operations R&D Issues

4.3.1 Software architectural and framework issues

The high-level workflow management functions of Pipeline Manager for processing data, Scheduler for managing the observation request queue, and Exception Handler for dealing with failures must work together in a "closed loop" manner that requires a challenging architectural design. In addition, the framework that defines the overall software environment must be in place before developers can begin to write consistent code. The Software Framework Definition will be a high priority for the R&D phase.

4.3.2 Software Product trade studies

The basic data processing steps are similar for many space-based and even some high-volume ground-based projects. Many software products and packages have been developed for performing these basic functions. Much of the Science Ops R&D effort will be devoted to evaluating these products for direct use or adaptation in SNAP. Re-use of debugged, "battle-tested" code is extremely cost effective where applicable. To this end, we have initiated a joint study with a team from the Space Telescope Science Institute (STScI) who developed data processing packages for the Hubble Space Telescope (HST). We are particularly interested in the following products:

- HST Pipeline Manager, OPUS
  This package is the "backbone" that manages the various modules that carry out the pipeline analysis functions. OPUS can manage several simultaneous pipelines and contains a graphical monitor of progress and problems.
- HST Scheduler, SPIKE
  This product assembles observation requests from approved science programs, examines the various constraints on observation requirements and spacecraft operational requirements, and applies an optimization algorithm to determine the "best" observational sequence.
- HST Data archiving and distribution product, DADS
  This product uses a catalogue archive to make data available to scientific queries. In includes "on-the-fly" recalibration capability.

The LBNL/STScI joint study will assess the applicability of these (and other HST) products for the SNAP mission. The deliverable will be a report that documents the trade studies, operations concepts, ground system architecture and estimated development costs.

In addition, we have also been in contact with the Infrared Processing and Imaging Center at CalTech regarding their packages and experiences with the 2MASS and SIRTF missions. We have had very preliminary discussions with some members of the Sloan Digital Sky Survey team and we plan to follow up with a visit to Fermilab for more detailed discussions.

The SNAP team is also working with the Supernova Factory (SNFactory) group to test some of these software products in a "real world" environment that has many similarities to the SNAP mission. The SNFactory uses the Near Earth Asteroid Telescopes to search for nearby supernovae. When the analysis pipeline identifies a candidate, a scheduler is used to queue spectroscopic follow-up on a University of Hawaii telescope at Mauna Kea. As part of the SNAP R&D program, we have ported OPUS to LBNL and started to evaluate its applicability as the SNFactory pipeline manager. In addition, we are helping the SNFactory team identify a scheduling package. We expect that this symbiosis will facilitate migration of SNFactory experience and even testbed code into SNAP and we consider it an important element of the R&D program.

4.3.3 Simulation R&D plan

Simulation is the link between the SNAP science goals one the one side and the instrument requirements and mission operational profile on the other. Many of these requirements and optimization studies have come from analytical techniques such as the Fisher Matrix formalism for error propagation. Specific questions were answered by very focused studies and calculations. While this has served us well in the past, some of the issues are so complex and inter-dependent that a full Monte Carlo simulation of the astrophysical and instrumental effects is required. We now have an end-to-end Monte Carlo that generates supernovae based on a few model parameters, propagates the light according to a given choice of cosmology, includes astrophysical effects such as dust extinction and weak lensing, and incorporates instrumental effects such as K corrections.

Instrumental effects are parameterized in terms of read noise, dark currents, point spread function, and calibration errors. For comparison with ground-based telescopes, the Monte Carlo also includes an atmospheric model with air mass and seeing effects. The result of the Monte Carlo is a Hubble diagram of corrected magnitude versus redshift. A cosmological fitter then extracts the cosmological parameters from the simulated Hubble diagram and comparison between the generated cosmology and fit cosmology tells us how well we can measure the science parameters of interest. The next step in the simulation R&D program will be to add the actual instrument emulation to produce pixel-level synthetic data. This synthetic data can then be fed to the analysis programs to extract the results. By contrast, the current version short-circuits the analysis by going directly to the parameterized result. To distinguish the two levels of simulation, we have dubbed the current parameterized version *SNAPfast* and we use the name *SNAPsim* for the yet-to-be developed version with full instrument emulation.

The specific simulation R&D plan then consists of:

- Completing the SNAP*fast* simulation studies
    - Some development is still needed to streamline the code and make it more efficient
    - Iterate the mission requirements and optimization for the ZDR and CDR
- Add full instrument emulation to develop SNAP*sim*
- Use SNAP*sim* to generate synthetic data for instrument tuning and code development

4.4 CDR planning

The ultimate deliverable from the R&D phase is the CDR. The R&D plan presented here is designed to lead to a credible scope, cost, and schedule for the Ground Segment part of the CDR. Preliminary results are expected for the ZDR approximately one year in advance of the CDR.

4.5 R&D deliverables

Table 18 lists deliverables for the Ground Segment R&D effort.

Table 18. Ground Segment deliverables schedule.

Deliverable	Completion
Simulation code complete	31-Mar-2003
Software framework definition complete	1-May-2003
Software Requirements Document	15-Aug-2003
Data Catalogue and Archive Specification	15-Dec-2003
Test bed reconstruction code	1-Jun -2004
BGS antenna upgrade specification	1-May-2004

Section 5. Telescope R&D plan

The R&D tasks associated with the SNAP Optical Telescope Assembly (OTA) are entirely driven by the need to prepare a thorough specification of the OTA performance requirements, the OTA interfaces, and the OTA acceptance test plan. This specification will in turn permit industry bidders to respond to our requirements with a minimum of time spent in questioning or clarifying the OTA requirements. We are aware that the design, fabrication, and test of a two meter class telescope is a project that can be expected to require about four years, a time scale that places the OTA procurement on the critical path for the planned SNAP mission.

Our view is therefore to streamline the OTA procurement by adopting four policies:

1. Our requirements will constrain the end-to-end optical performance, but allow vendor-specific freedoms in choice of materials, technologies, processing, and optical test facilities. In this way we will capitalize on the unique strengths and experience of the successful vendor(s).

2. Our requirements will be finalized after careful consultation with optical design and fabrication engineers whose credentials have been established through broad industry recognition. Toward this end we have support contracts in place with individuals and industry partners whose cumulative experience in large space optics is appropriate for a project of the scale of SNAP. A list of these engineering support personnel and industry groups is presented below.

3. Our requirements will be carefully prioritized with respect to potential tradeoffs that control the ease of manufacture, test, and integration. At present we are pursuing several trade studies discussed elsewhere. We anticipate that as further OTA system level constraints are better understood, our trade studies will grow, allowing us to properly assess and manage initiatives suggested by any potential OTA vendor.

4. Most telescope manufacturers are specialists. Some have particular expertise in mirror manufacturing while others excel in structure or integration. In addition, some NASA facilities have particular strengths in optical test and flight qualification work. Our procurement planning will therefore explore alternative routes: single prime vendor (with subcontracts), and combinations of suppliers and facilities. Our goal is to identify a route wherein the design, manufacturing, and test teams have the requisite experience to assure project success, while affording the customer sufficient visibility into the project's progress.

We do not anticipate that any OTA prototyping will be required during any phase of SNAP, since the optics technology is already established and proven far beyond the SNAP requirements. However the R&D phase provides the needed time span in which to conduct concept development and to refine our requirements. For this reason our engineering activities will be confined to two areas: the preparation of our Requirements Document, and engineering analyses supporting a collection of trade studies and risk mitigation efforts.

5.1 Requirements overview

Here we present a preliminary list of the requirements that will be specified during the R&D phase. These requirements will represent the chief result of our R&D study, and will be carefully reviewed by all members of the optics working group prior to the scheduled ZDR and CDR project milestones. The finished requirements document will constitute our primary vehicle for communicating the SNAP OTA description to potential vendors.

1. Optical performance:
    - minimum effective aperture and throughput
    - maximum permissible obscuration
    - instantaneous field of view requirement
    - Strehl ratio at 0.63 μm wavelength averaged over field
    - minimum ensquared energy for 10 μm pixels at 0.63 μm wavelength
    - minimum ensquared energy for 18 μm pixels at 1 μm wavelength
    - maximum allowed vignetting
    - min and max effective focal length at final focus
    - minimum throughput

2. Mechanical interfaces:
    - minimum & maximum mass, CG, and MOI as appropriate
    - allowed mechanical envelope compatible with launcher and S/C
    - anticipated static and dynamic loads imposed by launch
    - allowed frequency ranges & Q-factors for response to vibration
    - location and orientation and tolerance of final focal surface
    - locations and orientations of OTA focal-equipment interfaces
    - locations and orientations of S/C attach fittings
    - locations and orientations of electrical connectors
    - locations and orientations of GSE hoisting hooks
    - locations and orientations of shipping container attachments
    - locations and orientations of optical alignment GSE devices
    - GSE wagon
    - in-flight and ground adjustments for optical elements
    - structural stability requirements imposed by optical performance specifications

- provisions and/or interfaces for outer tube baffle

3. Electrical interfaces:
   - voltages, currents, heater resistances, signal levels for thermal control system
   - connector locations for OTA-supplied cabling & harnesses
   - drive electronics plan for on-orbit mechanical adjustments
   - GSE connectors harnessing and sensors for ground thermal & vibration tests

4. Thermal interfaces:
   - thermal heat loads during ambient ground testing, if any
   - identify cryocooling requirements during ground processing & testing
   - thermal environment expected on orbit
   - static & dynamic thermal loads imposed by S/C, detector system, other loads
   - thermal profiles anticipated during optional detector annealing cycles
   - transient thermal/structural response imposed by on orbit attitude changes

5. Other issues
   - OTA integration (structure + optics) facility: Vendor owned? Leased? NASA?
   - GSE optical test fixtures: OTA-vendor owned? NASA? Private/leased?
   - GSE thermal test chamber: OTA-vendor owned? NASA? Private/leased?
   - GSE vibration facility: OTA-vendor owned? NASA? Private/leased?
   - SNAP integration facility: Private? NASA? University?

As part of the OTA Requirements Document we have prepared a baseline optical system study that serves as an existence proof that our planned goals can be met. The present baseline optical system comprises a three-mirror anastigmat having a 2.0 meter aperture and an effective focal length equal to 21.66 meters, that decision being one of the trade studies identified below. The three-mirror anastigmat (TMA) layout is patterned after a family of analytic three mirror designs first explored in the 1972-1990 time frame. Its particular attractiveness for the SNAP mission is its ability to deliver a high quality image, averaging about 0.03 arc seconds RMS blur, over a large field of view amounting to about 1 square degree. This baseline system is an all mirror system that requires no refractive correctors. Further details can be found at the SNAP website http://snap.lbl.gov where detailed design specifications and performance estimates are presented.

5.2 OTA trade studies that were conducted during the pre-R&D phase

5.2.1 Optical configuration

Wide-field astronomical telescopes are not new. Beginning with the Schmidt survey telescopes deployed at mountaintop observatories during the mid-20th century, a variety of optical configurations have been proposed and many have been implemented. The usual goal is to achieve atmospheric-seeing-limited performance in at visible wavelengths. For such uses, refractive correctors are suitable, and therefore many of these wide field cameras utilize refractive elements at the entrance pupil (*e.g.,* the Schmidt) while others use refractive field flatteners (*e.g.,* the Sloan Digital Sky Survey instrument). SNAP however requires diffraction limited image quality, and operates over a much wider wavelength range, 0.35 to 1.7 μm. Refractive correctors cannot do this far more demanding job. Instead, to obtain a larger field than can be obtained with two-mirror Ritchey-Chretien optics, and to achieve higher resolution than can be obtained with two-mirror Schwarzschild optics, one must explore telescopes that have three powered mirrors. Three-mirror wide field telescopes have been discussed by many authors including Paul, Baker, Cook, Williams, Korsch, Angel, McGraw, Willstrop, *etc*. Most of these optical trains suffer from a large central obstruction in the pupil and from placement of the focal plane camera deep within the optical path. The obstruction leads to a significant loss of light gathering power and spatial resolution, and in space it is difficult to provide passive radiant cooling for the buried camera. One configuration, originally proposed by Korsch in 1981, eliminates both these limitations through the use of a small secondary mirror, of a tertiary mirror used as an inverting correcting relay, and of a focal plane located to one side where passive detector cooling becomes easy. For SNAP we have adopted this annular-field three-mirror anastigmat (TMA) configuration owing to these manifest advantages. In detailed studies during the pre-R&D phase we have found this TMA to be adaptable to a variety of lengths and focal ratios, allowing the diffraction pattern to be tailored in size for best science recovery. Details of our present baseline optical configuration, termed "TMA63," can be found at the main SNAP website http://snap.lbl.gov.

5.2.2 Warm optics vs cold optics

It is well known that if the principal optical elements are provided with heaters and thermostats to keep them close to room temperature in their flight environment, the testing can proceed within an ordinary lab environment with no need to establish a variety of thermal test environments. For example, HST and FUSE were designed in this way, and mirror temperatures are maintained within a few degrees of 290 K on orbit. However, owing to nonzero thermal emissivity, the thermal background seen by an IR detector will depend on the temperature of the optics. For this reason, a near-IR instrument will have a lower noise level if its telescope optics are allowed to cool to an equilibrium temperature that is somewhat lower, below 270 K. This will occur naturally if no heat is supplied to a well-insulated optic viewing deep space. However, cold optics would require cryofiguring of the three powered mirrors, which has direct cost and schedule impact. During the pre-R&D phase, we explored emissivities of various mirror coating materials and found that protected silver offers the best reflectance throughout our critical NIR bands, and furthermore has sufficiently low emissivity that our predicted thermal mirror background will be below the Zodiacal flux level provided that the mirrors are run below 290 K. Adopting a baseline temperature near 290 K will ease the mirror manufacture and test, yet not significantly impact the mission science.

5.2.2.1 Integrated focal plane *vs* separate focal plane instruments

It is well known that achieving a simple optical train (and a simple optical procurement specification) benefits from having a single input field and a single output field. Additional intermediate foci can be provided, but a cost is that the imaging performance of these fields may be strongly interdependent, and optical adjustments that furnish a good image at one focus may not furnish a good image at another focus. A particularly promising instrument concept, the Fully Integrated Detector Option (FIDO), places all SNAP sensors at a common focal plane, where they are tightly integrated and share mechanical structure, thermal environment, EMI environment, *etc*. The alternative is to have the various sensors located at distinct focal locations, with starlight delivered by pickoff mirrors and auxiliary optics. The total costs of the optical train, its testing, the instrument integration, and the flight operations scenarios all depend on this choice. During the pre-R&D period we explored these alternatives and adopted the FIDO option because it appears that all detector components can successfully operate at a common temperature and steps taken to simplify the optical system are certain to minimize the time spent on this critical path.

5.2.2.2 Low-CTE structure *vs* constant-T structure

During ground alignment and flight operations, it is vital to maintain precise relative positioning of our principal optical components in spite of environmental thermal variations. Two technical solutions to this problem are (a) the use of structural materials having nearly zero coefficient of thermal expansion, and (b) structural elements with a large CTE but maintained at a precise operating temperature by means of heaters, insulation, and high thermal conductivity links. During the pre-R&D phase we explored the use of various materials for the precision metering structure, and concluded that the strength, stiffness, manufacturability, and CTE of the best contemporary carbon fiber composites meet all our requirements. This decision allows a much-simplified active thermal control system. It is our present baseline choice for the metering structure.

5.3 OTA trade studies to be conducted during the R&D phase

5.3.1 OTA Vendor Capabilities Research

Determining the best route for procurement and test of the SNAP telescope is the single largest responsibility of the SNAP OTA team. During the pre-R&D period we visited a number of manufacturers of telescope optics and systems, and through a broad Request for Information we have received statements of capabilities from prospective vendors. During the R&D phase we shall extend this work and explore alternative routes for design, manufacturing, integration, and testing. It may prove useful to establish a strategic partnership with one or more NASA centers involved with flight optics to gain a broader perspective on the industry and to learn what existing test facilities would be most useful to SNAP.

5.3.2 Choice of mirror materials

A number of mirror materials have been chosen for the manufacture of large aperture space optics. Examples include:

- Corning ULE (Corning; Hubble backup primary mirror, many others)
- Fused Silica (Heraeus Amersil; many missions)
- SiC and C/SiC (several vendors in USA and France; HERSCHEL)
- Zerodur (Schott Glass Co., ORFEUS)

Each prospective OTA vendor has particular experiences with these materials, and we anticipate that the right material for SNAP will depend on our vendor's favorable experience working his material efficiently. Nonetheless, as customers, we need to understand industry experience with these materials in order to become educated buyers and properly assess the alternative processing techniques that prospective vendors may suggest.

5.3.3 Total cost & schedule vs. telescope aperture

As a general rule, telescope cost rises with aperture according to a power law whose index is about three. Nonetheless, for any given vendor, the actual cost function is a gentler rising curve, typically diameter to the power of 1.1, punctuated by a number of abrupt jumps corresponding to points at which larger test fixtures, grinding machines, *etc.* have to be built, borrowed, or procured. Accordingly we intend to work closely with prospective bidders to establish the best price/performance tradeoff with the mission science return.

5.3.4 Total cost & schedule vs. telescope wavefront error

Generally, cost and schedule requirements rise as allowable wavefront error is reduced, because additional cycles of measurement and figuring impose added labor. For this reason it is important to work closely with prospective bidders to better understand this tradeoff quantitatively and to identify the optimum specification for wavefront error.

5.3.5 Total cost & schedule vs. primary mirror thickness

As a general rule, a thicker mirror is heavier but stiffer than a thinner mirror. Consequently a thicker mirror may take longer to fabricate and would involve processing a larger amount of material, yet may provide considerable savings during the figuring, testing, and alignment phases of OTA production. These savings result from reduction or elimination of auxiliary 1 G support structures, air bags, *etc.* A further complication is that a heavier primary mirror creates added stresses in the OTA structural elements, influencing their size and strength requirements. These factors can best be understood by reviewing published analyses and performing finite element modeling for the primary mirror for a variety of potential lightweight structures, and assessing the degree of complication that thin and super-thin mirrors introduce. Preliminary efforts along these lines have already begun, and will be enlarged and extended under our R&D plan.

5.3.6 Prototype vs proto-flight OTA structure

The metering structure that locates the principal optical elements is obviously critical in establishing the strength and stability margins for the entire OTA. It may be advantageous to build one or more prototype structural items to permit early proof testing, thermal expansion testing, vibration-table modal testing, and gravity load response determination. The alternative is to build an early flight model of the OTA structure, perform qualification tests using dummy mass components, and (when qualified) upgrade this structure to flight status and flow it into the integration process.

5.3.7 *Preliminary test requirements and concept*

A major consideration in scheduling and pricing a large space optic is planning the sequence of accept/reject tests that each element of the optic will undergo, and devising a fair policy to accommodate manufacturing deviations that may occur in finishing one element by the appropriate modification of the successive downstream elements. A clear test plan, carefully explained in the OTA requirements document, and supported by established industry manufacturing policies, is a high priority for SNAP. We intend to create a test plan for the SNAP optics procurement that offers a prospective vendor flexibility in those areas that are non-critical, but that safeguard the key science driven requirements. Such planning will result from careful Q&A with established industry procurement consultants. This process has already begun. At present we have a four-point acceptance test plan:

1. Primary Mirror Metrology.
2. Primary/Secondary/Tertiary initial performance assessment.
3. Primary/Secondary/Tertiary w/flight OTA structure.
4. Final as-figured end-to-end performance testing.
5. System-wide thermal/vacuum testing.

This plan will be elaborated during the R&D study to include specific requirements for performance, vertical/horizontal gravity de-loading, interferometer *vs.* zone testing, full aperture *vs.* partial aperture testing, accommodation of nonconforming optical elements, and the inclusion of one or more compensators into the design to allow for better control of focal plane position, image surface tilt, and other concerns.

5.4 Long lead items

The entire OTA is a long lead item. The procurement process is expected to require about four years, making this single item the longest lead effort of the entire SNAP program.

In order to achieve the proposed schedule, the OTA team will specify and cost the OTA long lead items in time to order these items one fiscal year in advance of the proposed construction phase.

5.5 Risk assessment

We have identified several potential risk areas in the procurement of the OTA. Briefly, the risk areas that we have examined so far are the following.

5.5.1 Mirror fabrication/test risks

Any large glass item poses a potential risk of damage or fracture during ground handling, grinding, polishing, and testing, particularly where there may be extreme environmental tests performed using thermal stress, vibration, and mechanical shock. Fortunately, large astronomical telescope mirrors have been safely prepared and handled for projects far more demanding than the SNAP telescope optics. We are assured that a two-meter class telescope does not pose unusual risks, particularly when experienced optical manufacturers are brought on board to manage the production.

One risk area is the possibility of serious figuring errors being introduced into one or more of the SNAP telescope optics. We plan to guard against this eventuality by implementing (as a minimum) a four-stage test plan, in which each mirror element is tested individually, then in concert as the OTA is assembled. We understand that this progressive test plan, finishing with full aperture end to end test performance while mounted in the flight OTA structure and supported appropriately against 1 G deformations, provides the needed assurance that a manufacturing fault will be discovered before the SNAP mission is launched.

Does the launch stress environment pose a threat to the OTA? We now understand that a number of two meter class telescopes have been safely launched, using industry-proven three point support systems. These mirror support structures are fully qualified for optical elements in our mass class and have proven themselves on a variety of missions. We intend to capitalize on this experience and adopt proven structural mirror support methods for the SNAP mission.

Can the thermal environment pose a threat to the on-orbit OTA performance? We believe that by implementing a comprehensive thermal-vacuum test plan we can quantify the thermal performance of the OTA prior to flight. In addition, we anticipate that judicious use of *in situ* electrical heaters and thermostats will allow us to understand, and overcome, any reasonable thermal off-nominal situations.

5.5.2 Mechanical structural risks

Any large mechanical structure loaded with a ton (or more) of equipment may fail in a variety of ways when presented with the acceleration and vibration environment of a space launch. We plan to mitigate these risks by adopting a comprehensive plan for piece part testing and for qualification of materials, processes, and finished structures. In the aerospace industry it is common to perform static and dynamic load testing to establish measured safety factors for the mechanical elements of the OTA. In addition, TMAs have 13 critical adjustments for focus and collimation, some subset of which are to be motor-driven on orbit. The motorized actuators for these adjustments will require their own qualification and test program during the fabrication phase of the SNAP project. We anticipate preparing a Finite Element Analysis of the principal flexural modes of our adopted OTA structure, and computing the expected loads and margins for a variety of launch environments, to better understand the tradeoffs associated with the alternative structural concepts.

5.5.3 End-to-end performance risks

A key issue with regard to acceptance testing is the fact that all acceptance tests are necessarily performed in a 1 G environment, while the only performance that affects the science is the performance that is manifested in a 0 G environment. For this reason we anticipate the need for careful planning with regard to the de-loading of the principal optical and structural elements. In particular, a lightweight primary mirror is certain to deform significantly unless it is designed with extremely high stiffness, particularly in the azimuthal deflection mode. An obvious trade is to compare the expected deflections for various mirror thicknesses, stiffness, and cost, while factoring the test plan complications that arise from the 1 G test environment. It is anticipated that full-aperture end-to-end testing will be required, performed interferometrically, or by null test, or by zonal test. Moreover, the thermal-vacuum acceptance tests will have to be planned with careful consideration of the limited availability of T-V facilities that allow full aperture optical performance evaluation. With a full understanding of these important cost and schedule constraints, the SNAP team will assess various de-loading strategies and thermal stress test plans using FEM techniques.

5.5.4 Schedule risks owing to requirement revisions

The OTA delivers its image to a science instrument package, and the details of the final focal surface (plate scale, field, focus position) drive the telescope design. By the time that bids are sent to prospective vendors we expect that our exact image requirements will be fixed. During the R&D phase, however, changes in this instrument package may occur. We intend to provide the manpower necessary to track instrument revisions and maintain the OTA requirements document in an appropriately updated manner.

5.5.5 Error budgets

The manufacturability of the OTA will depend on an appropriate manufacturing error budget, in which a variety of potential error magnitudes from figuring, fixturing, assembly, and test are correctly distributed. These decisions will hinge partly on the experience of the optical fabrication partner whom we choose and partly on the judgment of our OTA team members. We intend to create a preliminary manufacturing error budget as part of our OTA Requirements

Document, and invite prospective vendors to comment on our assessment and/or provide alternative error budgets based on their experience. In this way we intend to be flexible with regard to individual error terms yet remain relatively inflexible with regard to the overall performance requirements.

5.5.6 Contamination control

During manufacture, test, shipment, integration, and launch the OTA will be subject to a number of potential contamination hazards. We intend to develop a contamination control plan in concert with our OTA supplier that will safeguard the cleanliness of the optical surfaces during all phases of the program.

5.6 Prospective OTA vendors

Because the success of the OTA procurement for SNAP hinges on prompt effective participation by an industry partner, it is reasonable to ask which potential industry leaders are known to have the necessary experience and facilities to allow this project to proceed efficiently. In consultations with other space astronomy groups we have identified a small number of potential vendors who can manage all or part of the OTA project as we have envisioned it. In alphabetical order, our current list of potential vendors includes:

- Ball Aerospace Systems Division (Boulder CO)
- Boeing SVS (Boulder CO)
- Brashear LP (Pittsburgh PA)
- Composite Optics Incorporated (San Diego CA)
- Goodrich (Danbury CT)
- Kodak (Rochester NY)
- Lockheed Martin Missiles & Space Company (Sunnyvale CA)
- SAGEM/REOSC (France)

5.7 Schedule

OTA development deliverables dates are shown in Table 19.

Table 19. OTA deliverables schedule

Deliverable	**Completion**
Trade study: aperture .v. cost/schedule	1-Feb-03
Trade study: wave front error .v. cost/schedule	1-Mar-03
Trade study: primary thickness .v. cost/schedule	1-Apr-03
Trade study: prototype .v. protoflight plan	1-May-03
OTA Performance Requirements (Zeroth Order)	1-Jun-03

OTA ZDR Package	1-Aug-03
OTA Long Lead Procurement RFI	1-Aug-03
OTA Long Lead Procurement Cost Envelope	1-Sep-03
OTA Long Lead Procurement Budget Request	1-Oct-03
OTA Manufacturing and Test Requirements	1-Feb-04
OTA Vendor Manufacturing RFIs	1-Mar-04
OTA Vendor Proposal Review / Cost Bracketing	1-Jun-04
Systems Requirements Review	1-Jul-04
Concept Study Report	1-Aug-04

Section 6. Spacecraft R&D plan

The spacecraft provides the mechanical infrastructure to support the optical telescope and instrumentation complement. Its electrical power system includes solar arrays and circuits for the battery and battery charge control, providing power to operate SNAP. Its communication system provides command and telemetry functions. It contains an attitude control system (ACS) to orient the telescope for scientific viewing, and propulsion to unload the momentum wheels. In addition, the spacecraft will provide some control and memory functions. The thermal environment of the SNAP telescope and instruments will be controlled through a combination of passive and active thermal management provided by the spacecraft, *e.g.*, radiators, baffles, shields and heaters. The SNAP spacecraft requirements fall within standard spacecraft capabilities, and the design presents little risk to the project. The single most demanding requirement on the spacecraft is that it must be able to point with high accuracy and stability.

The intent of the SNAP Project is to team with a single aerospace industrial contractor who would supply the spacecraft portion of the observatory system as an integrated package. This vendor may perform all or a portion of the Integration and Testing task. The primary spacecraft-related task during the R&D period is to clearly define the observatory system requirements and architecture, and to delineate exactly what is included in the spacecraft portion of the task.

We intend to utilize the Goddard Space Flight Center's Rapid Spacecraft Development Office (RSDO) to select an industrial teaming partner for SNAP just after CD1. While each of the spacecraft in the RSDO catalogue are fixed in price, we assume at this point that some of the SNAP requirements may require some tailoring of spacecraft systems. Thus, we intend to work with the RSDO spacecraft contractors to develop a strawman design together with a detailed cost and schedule for CD1. After authority is granted to proceed after CD1, we will have RSDO select the spacecraft and required options.

To accomplish this goal, we will devote one year to the performance of a number of analyses and trade studies, in the process developing a clearly defined spacecraft system and set of requirements. Thereafter we will be in a position to select a teaming partner to work on the spacecraft strawman design and develop a detailed cost in support of the implementation phase. Below we describe the spacecraft-related analyses and trade studies to be completed during the R&D phase. Several aspects of the spacecraft, such as structural and thermal design, are also discussed in Section 7, R&D System Engineering.

6.1 Spacecraft related analyses and trade studies

6.1.1 Observatory structural design

The design of the observatory primary structure is strongly constrained by payload requirements including maintenance of the OTA alignment, payload thermal control, and a requirement for modularity to allow the instrument to be assembled and disassembled for testing and trouble-shooting. This leads to the use of a custom observatory structure design driven by payload requirements rather than the use of a "standard spacecraft bus" which undergoes minor modifications to accommodate the payload. In an optimized design, the spacecraft portion of the structure may vary from nothing beyond the housings of the spacecraft components themselves, to a load bearing structure which includes the launch vehicle attach ring and a tie point to the payload which transfers the entire payload reaction to the launcher. A relatively detailed observatory design is required to settle the question of what form the spacecraft structure will take, and is also needed before the thermal design can be completed.

A less obvious but very important requirement is that the mechanical layout be closely iterated with the integration and test plan so that sub-assemblies can be removed for testing and debugging without disturbing portions of the system that already have been tested and installed.

These issues are discussed in more detail in Section 7, R&D System Engineering.

6.1.2 Attitude control system (ACS) preliminary system design and error analysis

Attainment of 0.03 arc-second 3-sigma pointing of the telescope is essential for the full completion of the SNAP mission science goals. While pointing accuracy at this level and better has been accomplished on a number of previous spacecraft, (*e.g.,* Hubble at 0.005 arc-seconds with a significantly less rigid structure, or the Remote Mirror Experiment) this requirement is at the high end of standard spacecraft practice. We wish to insure early in the program that a viable ACS solution using standard components exists for the particular mechanical properties and disturbance sources of the SNAP mission.

During the R&D phase we will create a computer model of the SNAP system in two phases. In the first phase, we will concentrate on static performance, creating a dynamic model including ACS feedback, implement Kalman filtering and explore its optimization, gather and integrate wheel dynamic noise disturbance spectra, and include FEM structural resonances, where needed. In the second phase, we will concentrate on dynamic performance, upgrading the computer model to include telescope flexural behavior, installing a simplified fuel slosh model, exploring large angle settling behavior, and estimating maneuver times required for model mission profile. First results from the modeling will be available within 9 months. The inputs to the model will be continuously updated throughout the program as the designs of the various sub-systems are refined.

The model will determine the attitude determination capability of a self-contained system, i.e. one that does not receive attitude information from the Optical Telescope Array (OTA). By including a path from a model OTA star guider to the ACS system, we will develop an understanding of the relation between the requirements on the OTA star guider system (*e.g.*, update rate) and the ultimate pointing capability of the integrated observatory system.

6.1.3 Propulsion system specification and analysis

The SNAP spacecraft will use a monopropellant hydrazine system to unload the reaction wheels used by the ACS system and to meet the NASA debris requirements. Since the requirements on this system are well defined and easily met, this system is not expected to be a risk area or one requiring any technology development. However, portions of this system interact with other systems in the observatory in ways that have a bearing on the successful operation of those systems. In particular, slosh in the propellant tanks could have a significant effect on the operation of the ACS system, and mechanical properties of the thrusters and their associated plumbing may significantly impact the modularity and testability of the observatory.

For this reason we will create a propulsion system concept and generate a set of specific tanks, thrusters, valves, and plumbing to be used on the SNAP observatory. From this we will generate mechanical models of the tanks to be used in the ACS model.

6.1.4 Power system components specification

Since power system technology is very well developed, the system is a low risk area and will use components with a long history of space flight use. What is usually the most difficult part of the power system, the solar array panels, is relatively straightforward for SNAP because the payload thermal system will provide a large area that is always pointed toward the sun within 45 degrees. The thermal design task will include the provision of flat areas for mounting solar cells with suitable capability for dumping waste heat. During the R&D phase we will refine the power estimates and service requirements and then refine the strawman power system design to include the battery type and requirements on the control unit.

6.1.5 High gain antenna and gimbal specification and analysis

The RF performance requirements for the High Gain Antenna (HGA) will be determined in trade studies with the ground systems and orbit analyses. These trades will determine the size of the steerable antenna needed to communicate SNAP data to the ground at high rates. In addition, these studies will determine the pointing accuracy required.

The detailed mechanical properties of the HGA and its associated gimbal assembly are a critically required input for the ACS model. During the R&D phase we will identify manufacturers for these units and determine their mechanical properties for use in the ACS model.

6.2 Schedule

Deliverables and schedule for the spacecraft R&D are contained in the discussion of System Engineering, Section 7 below.

Section 7. System Engineering R&D plan

The SNAP Project System Engineer (PSE) is responsible for the coordination and management of all design and engineering activities involved in the development of the SNAP Observatory. The PSE task is to insure that the spacecraft, telescope, instrumentation suite and ground data system form an integrated and consistent design that will successfully meet the requirements placed on the project.

During the R&D phase, the primary engineering activity is to select and refine a conceptual design approach for the observatory and mission that will meet the SNAP high-level mission requirements, and to perform trade studies to optimize the approach. Our intent is to concentrate effort in those areas requiring the greatest innovation or posing the greatest potential risk, and to postpone the development of detailed plans for activities that routinely have been accomplished on many previous spacecraft.

7.1 System engineering R&D studies

7.1.1 Structural design study

The design for the observatory structure requires the establishment of an initial set of requirements imposed by the telescope and instrumentation suite. This design has already started, and will be continued and iterated during the R&D phase. The design approach is to start with the metering structure that supports the 3 mirrors of the TMA along with any needed flats and the optics bench. This will then be integrated with the supports needed for light baffles and thermal shrouds, and connections to the launch vehicle interface ring. Finally, provision is made to support the electronics modules and the spacecraft components including those of the ACS, propulsion, and communications systems. The solar array will be mounted on the warm side thermal shroud that is always aligned generally perpendicular to the sun.

An additional task of the observatory structure design study will be to define the extent of the "spacecraft" portion of the observatory and hence what structural components would be provided by an aerospace industry teaming partner as part of the spacecraft procurement.

A mathematical model of the structure will be developed in parallel with the structural design, and will be used to support the thermal design and ACS analyses as well as verifying the integrity of the structure.

The layout, design, and analysis will be done by a team of SNAP engineers.

7.1.2 Thermal design studies

The thermal control task is closely related to that of the structural design and so activities in both areas will proceed in parallel with constant iteration between them. Thermal control is of extreme importance for the proper operation of the payload, particularly in three areas:

- The maintenance of the figure and focus of the OTA;
- The maintenance of the operating temperature of the focal plane sensors and control of stray radiation into the IR sensors by nearby structure;
- The reduction of thermally induced disturbances that will compromise the pointing capability.

To address these critical issues, we will model a detailed thermal control system for the observatory. This task will include development of the control strategy, design of the structural elements and coatings, baffles, heat pipes, *etc*., and modeling of the completed system. Due to the necessarily light and less rigid structures required for thermal baffles and shields, the mechanical properties of the system will be an important input into the ACS model. We will also develop a layout for the solar panels that includes a system to maintain the cells within their optimum operating temperature range.

By the end of the R&D phase, we expect to have a design concept with sufficient detail to make a mathematical model of the system that will demonstrate that operation of the observatory will meet the SNAP mission requirements.

7.1.3 Payload and observatory integration and test plan

Because of the stringent pointing requirements on the SNAP telescope and the fact that the system will be designed to work in a zero gravity environment but must be tested in a 1 G environment, the I&T task will be at least as challenging as that of the design and fabrication of the observatory. The I&T plan is driven first by the requirements of the OTA manufacturing and testing, and second by the assembly and test of the integrated science payload including the focal plane sensors. Because the OTA components provide the major testing challenges, the OTA team will develop the outline of the I&T plan.

During the R&D phase, manufacturing and test plans for each candidate mirror fabrication process will be developed. Methods of performing each required test will be identified, and a plan will be developed that includes the identification or design of the facilities required to accomplish the tests. We anticipate that dedicated custom equipment will have to be developed which may include modification of existing facilities. An important part of the process will be an evaluation of what tests can practically be done, and in what areas we must rely on analysis (*e.g.*, how can we test the attitude control system?).

By the end of the R&D phase we will have a definition of each of the optics related tests, the order in which they will be done, a definition of all manufacturing and assembly steps, and a preliminary definition of the facilities requirements and an evaluation of possible ways to acquire them.

7.1.4 Mission analysis and orbit-debris strategy

A key element in the SNAP mission strategy is to provide a suitable platform from which the science measurements can be made using a reasonably priced launch vehicle. We plan to use a highly elliptic, 3-day orbit which will be synchronized so that the perigee over earth is centered about the primary ground station. This is achievable by a several available launch vehicles.

Since this orbit crosses the orbit of geosynchronous satellites, the mission may be required to deorbit at the end of its life. During the R&D phase, we will determine the best approach to satisfying the orbital debris requirements.

At the end of the R&D phase we will have a precise orbit definition, and the set of requirements on the ACS, propulsion, data and command systems needed to support the orbit insertion. Any impacts on the ACS system will be iterated into the ACS modeling effort that will be carried out in parallel.

7.1.5 Launch vehicle requirements

The refined definition of the observatory structure, mass, pointing requirements, and orbit analysis developed by the System Engineering activities performed during the R&D phase will result in a further understanding of the requirements on the launch vehicle. We will use this information to make a preliminary selection and to initiate preliminary discussions with the vendor regarding availability and cost.

7.1.6 Reliability analysis

During the R&D phase the System Engineering group will perform a first order reliability analysis for the observatory system with an emphasis on development of a plan for the use of redundancy and elimination of single point failures. This information is essential to properly specify requirements on the spacecraft and to guide the layout of the payload electronics and data system. This activity will be done primarily by SNAP engineers with assistance from outside consultants.

7.1.7 System engineering tracking documents

During the R&D phase we will set up a Configuration Control system for the project and initiate a formal system for the tracking of mechanical, electrical and thermal properties of each component and subsystem. We will also set up systems for tracking computing, data and memory requirements.

7.2 Schedule

The system engineering deliverables schedule is shown in Table 20.

Table 20. System engineering deliverables schedule.

Deliverable	**Completion**
L2 Requirements (Systems)	1-Apr-03
L3 Requirements (Subsystems)	1-Jul-03
Draft Requirements Review	1-Jul-03
Operations Concept	1-Jul-03
Zeroth Order Design Report	1-Aug-03
ACS Model Phase I	1-Oct-03
Power / Thermal Systems Concept	1-Oct-03
Propulsion System Concept	1-Nov-03
HGA Concept	1-Dec-03
Interface Definition	1-Jan-04
Risk Assessment	1-Feb-04
SR & QA Requirements	1-Mar-04
I&T Plan & Schedule	1-Apr-04
ACS Model Phase II	1-Apr-04
S/C Studies RFI	1-Apr-04
S/C Studies Results/Cost Bracketing	1-Jun-04
Structural Model	1-Jul-04
Launch Vehicle Requirements	1-Jul-04
Systems Requirements Review	1-Jul-04
Concept Study Report	1-Aug-04

Section 8. Management During R&D Phase

This summary presents the major SNAP management and systems engineering milestones and deliverables closing the R&D and conceptual design phase of the project (through CD0 to CD1).

Proper management and systems engineering activities are crucial to the development of a good project concept and implementation plan. Proper technical and organization groundwork during the concept phase will make possible the straightforward and effective implementation of the project and enhance the probability for mission success.

Management plays a supportive role in Research and Development, providing resources as needed to accomplish an agreed-upon set of research tasks. In contrast to development phases, management neither dictates the schedule nor demands strict adherence to a specific budget. Rather, management works with the PI, Systems Engineering and R&D developers to prioritize those results that can be obtained for the project with reasonable overall cost and appropriate schedule. It is management's goal to achieve the lowest possible mission risk by thoroughly investigating new technologies and assessing their readiness before proceeding into fabrication.

In parallel with the R&D activities, SNAP management is responsible for coordinating the scientists and engineers in the development of the SNAP project concept, in determining its schedule and its implementation cost. These tasks are further defined below. The groundwork is prepared for successful project execution during the conceptual design phase.

8.1 Management Elements

Project management during the conceptual design phase is carried out by the Project Directorate, including advisory bodies; the Systems Engineering Office; and the Project Office.

8.1.1 The Principal Investigator

The Principal Investigator / Project Scientist has principal responsibility for the project with regard to its scientific mission. The Principal Investigator (PI) is the spokesperson for the project and oversees the scientific planning. He leads the activities of the collaboration, the scientific working groups and receives advice from the Collaboration Council and the External Science Advisory Committee.

The PI will maintain frequent contact with the members of the Collaboration Council, from whom he will obtain advice on all major collaboration issues.

8.1.2 The Project Directorate

The body responsible for technical, scope, schedule and cost execution of the project is the Project Directorate. It consists of the Project Director, the Project Manager, and the Deputy Project Manager. The Project Office and the Systems Engineering Office assist the Project Directorate in this regard. The Project Directorate works closely with the Principal Investigator to maximize the scientific return of the project.

The Project Director has responsibility for the direction of SNAP project activities. The Project Director coordinates the R&D, conceptual design process, and works closely with the Principal Investigator to ensure the scientific success of the project. On financial matters, the authority of the PD will be consistent with the requirements of the funding agencies and will include responsibility for keeping the agencies informed about the status of the project.

The SNAP Project Manager (PM) is responsible to the PD for the execution of the project within the schedule, cost and resource constraints available. With support from the Project Office (PO) and the Systems Engineering Office (SEO), the PM will establish tasks, work statements, Memoranda of Understanding (MOU), deliverables, schedules, and changes to those elements.

The PM is responsible for day-to-day project management, including project status; risk management; documentation, cost and schedule tracking; subcontract management; and coordination with team members. The PM is the focal point of communication for project construction.

The PM will be responsible for establishing a baseline project plan. This plan will establish the schedule, cost phasing, and resource needs to carry out the SNAP project consistent with experiment science requirements. This proposal is the first step in defining the project plan. The complete project plan requires the approval of the PD, and the agencies, before being accepted as the baseline.

The SNAP Project Systems Engineer (PSE) is responsible to the Project Manager and Project Director for the engineering of the project and the organization and management of the engineering resources. The PSE is responsible for the development of cost and schedule and the optimization of the project through the Systems Engineering Office (SEO). The PSE will establish specifications, requirements, interfaces, and work statements, and is responsible for overseeing configuration tracking as appropriate during the conceptual design.

8.1.3 Management Panel

The management of SNAP currently is composed of scientists and engineers from both the University of California Space Sciences Laboratory (SSL) and from Lawrence Berkeley National Laboratory (LBNL). In order to permit the efficient functioning of the management team and provide a unified approach to oversight and access to resources, and to enhance communication, the two institutions have formed a Management Panel for SNAP. Currently serving on this board from SSL are: Prof. Robert Lin (Director SSL), Peter Harvey (outgoing SNAP Project Manager), Henry Heetderks (SNAP Systems Engineer and incoming SNAP Project Manager), and David Pankow (SNAP Systems Engineer). Serving from LBNL are Saul Perlmutter (SNAP Project Scientist and PI), Michael Levi (SNAP Project Director and Co-PI), Pier Oddone (Deputy Director LBNL), Kem Robinson (Project Integration & Management Officer), Prof. James Siegrist (Physics Division Director), Richard DiGennaro (incoming Deputy Project Manager), and Jay Marx (ex-officio). This board currently meets biweekly to discuss joint organizational and planning issues.

8.1.4 Collaboration Council

The SNAP Collaboration Council is composed of a lead scientist from each of the collaborating research institutions. The Collaboration Council along with the Principal Investigator establishes scientific goals and objectives of the SNAP project. It advises the Principal Investigator on all scientific, collaboration and collaborating institution matters of the project. It will develop a policy for membership and for publication. The Council will decide on controversial issues within the collaboration by consensus or by voting.

The Principal Investigator and the Project Director are ex-officio members of the Council. Official Board meetings will be held on an as needed basis and no less frequently than twice a year.

8.1.5 External Science Advisory Committee

The External Science Advisory Committee (SAC) will be comprised of several external outstanding individuals from the US, Europe, and elsewhere with expertise in the various facets of the SNAP science.

The SAC will meet with the SNAP collaboration to review the SNAP science objectives. These reviews will be held in the form of short briefings given by members of the SNAP science teams. The SAC will provide the Principal Investigator and the Program Directorate with a summary report on their recommendations, suggested plan of action, and observations.

8.1.6 Project Technical Board

The SNAP Project Technical Board (PTB) is responsible for working with and advising the Project Directorate with respect to the execution of the project as a whole. Its membership consists of the Project Manager and Engineer, leads from the Systems Engineering Office, the Project Office, the Safety, Quality, and Reliability Office, the individual systems managers and additional members as deemed appropriate by the Project Directorate.

The PTB shall meet on a regular basis to discuss technical, cost and schedule issues and will form the basis of the Change Control Board (CCB). Its main goal is to help ensure that all systems of the project are being adequately integrated and executed toward the scientific and technical goals of the project within the constraints of budget and schedule.

8.1.7 Systems Engineering Office

The Systems Engineering Office (SEO) is charged with developing and maintaining the system hardware and software requirements and specifications. The SEO reports directly to the Project Systems Engineer within the SNAP Project Directorate. The SEO has responsibility for system level issues. During conceptual design, the SEO primarily will be concerned with top-level requirements flow-down so that design and planning decisions are made with overall systems considerations in mind. Its other key role is the development of interfaces between the various systems. As such, the SEO will be working continuously with system managers to ensure that interfaces are properly defined and that technical issues affecting more than one system are resolved efficiently and effectively.

Requirements, specifications, and Interface Control Documents (ICD) will be entered into configuration management by the end of the conceptual design phase. Systems management will be performed through regular reviews of the design activity.

8.1.8 Project Office

The Project Office (PO) is responsible for monitoring the technical scope, cost and schedule performance of all portions of the SNAP project and providing assessments to the Project Directorate. The Project Directorate then provides timely and complete reports to the sponsoring entities. The Project Office will maintain the SNAP master resource-loaded schedule that is capable of determining and monitoring the progress of the project.

8.2 Management Processes

Beyond day-to-day oversight of the R&D program, the main activities of the management group and systems engineering group include requirement specifications and development, development of collaboration agreements, systems engineering, oversight of cost and schedule development, risk assessment, and generation of regular progress reports. Each of these areas is discussed below, followed by a summary of the major milestones and deliverables during the conceptual design phase.

8.2.1 Requirements and specifications development and control

A top-level project scientific requirements document will be developed during the initial phase of the program by the project science team. Systems requirements and definition are the responsibility of the Project Systems Engineer and the Systems Engineering Office. The SEO will lead the definition of lower level system and subsystem requirements using a documented flow-down process. All hardware and software elements of the SNAP system will be defined in these specifications. At the appropriate point in the program, the specifications will be placed under configuration control, after which changes will be made by means of formally controlled Engineering Change Orders (ECO) that assure proper review by all affected project elements. Updated documentation will be made available to all affected parties. A straightforward system of verification of the latest current version of any project document will be continuously maintained and readily accessible to all.

8.2.2 Management of collaboration agreements

Memoranda of Understanding (MOU) will be written between the institutional members of the SNAP collaboration and the Project Directorate. These agreements will cover the cost, schedule, and technical scope of deliverables, and resources to be provided by respective collaborators and the resources to be provided by the Project Directorate. The MOUs will specify inter-institutional conduct within the collaboration as well as the scope of efforts for the respective collaborators. The MOUs will be reviewed along with progress each year as part of the yearly financial planning cycle.

The members of the SNAP collaboration will subcontract to LBNL, or, if required, to UCB. The subcontract will be established by means of a proposal that contains a statement of work, technical requirements, specifications (where appropriate), schedule, and cost of elements of the deliverables. A subcontract manager affiliated with the SNAP project office will monitor progress and serve as the point of contact for contractual matters between the project office and collaboration institutions. The subcontract manager reports to the Project Manager.

8.2.3 Management and performance of systems engineering

The SNAP Project Systems Engineer has primary responsibility for assessment of all systems-level issues (the Project Director is ultimately responsible for decisions, with input from the PI). It is critical in this process to view all elements of the SNAP project as a combined entity and to properly allocate requirements and design approaches across the entire system. As part of the conceptual design study, the Project Systems Engineer will develop a Systems Engineering Management Plan that will serve as the framework and control for all subsequent work and trade-offs. The evaluation criteria for examining the trade-offs will be developed during this same phase, very early in the design process. Additionally, the SEO will be primarily concerned with the development and analysis of top-level requirements and their flow-down. Systems models will be developed and the initial trade studies will be performed. System operation will be considered so that design decisions are made with the end user in mind. The other key role of the SEO is in the development of interfaces between subsystems. As such, the SEO will work continuously with system and subsystem managers to ensure that interfaces are properly defined and that technical issues affecting more than one system are resolved efficiently and effectively. An important product of the initial phase is the establishment of initial system architecture and initial subsystem interface definition.

8.2.4 Cost and schedule development

During the conceptual design phase, several critical activities must occur. The SEO management plan must be developed. The requirements development and analysis must be started and the appropriate evaluation criteria must be identified. A number of important trade-off studies must be performed and analyzed, as they will determine basic aspects of the system. The risk management plan with ties to the R&D plan needs to be developed and implemented. The initial system architecture and interface definitions must be established.

During the conceptual design phase, the initial R&D and technology plans must be perfected and executed including the necessary prototyping efforts and associated test plans. The engineering concepts must be developed, and prototype development and tests must occur. Also crucial during the conceptual design is the development of the detailed R&D plans that extend beyond the conceptual design phase into the preliminary design phase.

Additionally, the SNAP Project office will develop the management and staffing plans; initial MOUs between collaborators for the preliminary design phase; the complete Work Breakdown Structure (WBS); the cost estimates; and the preliminary overall integrated project schedule.

With the movement into Conceptual Design, activities shift from a definition and exploratory phase to one on concerted systems, project, and technology design and development. The conceptual design of all subsystems is completed and a Conceptual Design Report is reviewed. The final technology and development plans with milestones and decision points are completed.

Within the SEO and PO areas the system architecture is finalized. The subsystem requirements are assigned. The subsystem interface definitions and formal risk analysis are completed. The configuration management and change control plans are finalized and implemented. The final project planning, system safety, reliability and quality assurance plans are completed. The cost estimate (cost bracket), contingency analysis, master resource loaded project schedule, and WBS are completed and prepared for review.

During conceptual design, the acquisition strategy is prepared. This strategy sets forth the management approach that will be used to ensure that the project contract or system of project contracts satisfies the approved mission need. The acquisition strategy can be part of the mission need document, a separate document, or a part of the Acquisition Plan.

8.2.5 Risk assessment

The first step in the management of risk is its assessment. This is done initially in conjunction with the estimation and determination of the work to be done. Each element used in costing is assessed and scored as to its stage of development and potential impact on the project. Specifically, each element is rated for design/approach maturity, complexity, dependency, technical development, cost uncertainty, and potential schedule variance.

The data thus obtained are then scored following procedures adapted from previous large H.E.P. project and NASA approaches. Calculations are then done on the assessed risk score to determine an appropriate level of cost and schedule contingency. In parallel, possible scope contingencies are identified with decision points established where technical trade-off choices must be made.

Once the project is under way, issues identified with risk to the project are monitored and contingency is allocated where necessary. In addition, reliability assessments and trade-off studies also seek to minimize incidental as well as project risk. It should be stressed that risk management is not merely the initial allocation of funding contingency to various tasks and subtasks. Complete risk management is an ongoing effort throughout the life of the project and involves developing not only the funding contingency but also the schedule and technical contingencies.

8.2.6 Progress reports

Financial and project reports will be submitted to the funding agencies as required. Technical progress reports will be submitted to summarize progress, concerns, problems, changes, and plans for the next period. In addition, frequent contact with the agency technical monitors will be the project's standard practice.

8.2.7 Activities

Key activities during the conceptual design phase of the project are:

- Perform project & detail design phase technical and programmatic risk analysis
- Develop system-level functions and requirements
- Identify long-lead procurements
- Develop project execution plan for preliminary design
- Set project execution strategy
- Review design alternatives
- Identify project standards and procedures
- Develop preliminary design phase budget and schedule
- Develop total project cost and schedule range
- Identify current and two fiscal year funding requirements

8.2.8 Major reviews

Major reviews are:

- Draft Requirements Review
- System Requirements Review
- Conceptual Design Review

8.2.9 Major deliverables at CD-1

Major deliverables at CD-1 are:

- Acquisition Plan
- Project Expectations Summary
- Statement of Work
- NEPA Documentation
- Systems Engineering Management Plan
- Conceptual Design Package
- Preliminary Project Execution Plan
- Preliminary Hazard Analysis Report
- Preliminary Team Execution Plan
- Risk Management Plan
- Preliminary Design Phase Budget & Schedule
- Verification of Mission Need
- CD-1 Package
- Total Project Cost & Schedule Range

8.2.10 Deliverables during the period

Table 21 lists major deliverables generated during the period.

Table 21. Project management deliverables schedule.

Deliverables	Completion
Zeroth Order Design Report	1-Aug-2003
Draft Requirements Review	1-Aug-2003
Long Lead Procurement/Budget Request	1-Oct-2003
Systems Engineering Management Plan	1-Feb-2004
Performance Assurance Implementation Plan (Draft)	1-Feb-2004
Risk Management Plan	1-Feb-2004
OTA & S/C Study RFP	1-Feb-2004
OTA & S/C Study Contracts	1-Apr-2004
Preliminary Project Execution Plan	1-May-2004
Preliminary Hazards Analysis	1-May-2004
Systems Requirements Review	1-Jul-2004
Conceptual Design Report/Review	1-Aug-2004

SNAP Conceptual Design Phase Organization

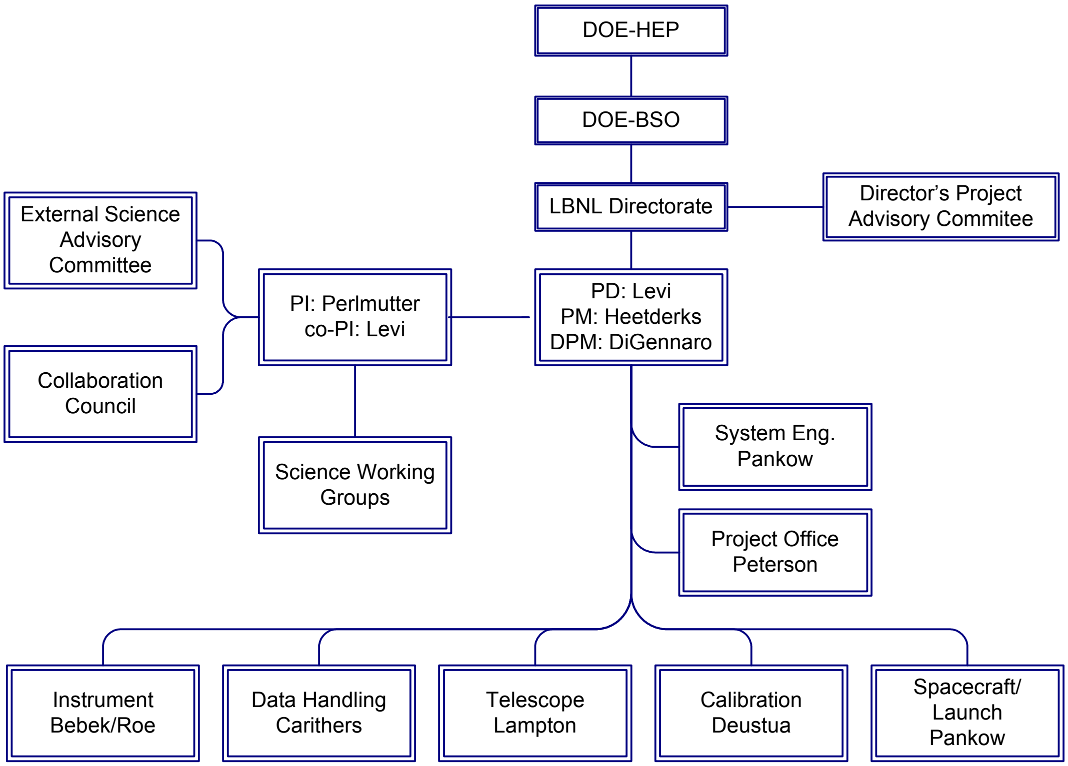


Figure 66. As can be seen in the project organization chart, the SNAP project is divided into its principal systems and subsystems beneath the Project Directorate. Each major system has a designated System Manager who is responsible for the successful development and completion with compliance to system and scientific requirements of the system within budget and schedule constraints.